Theory and Modelling of Coronal Wave Heating

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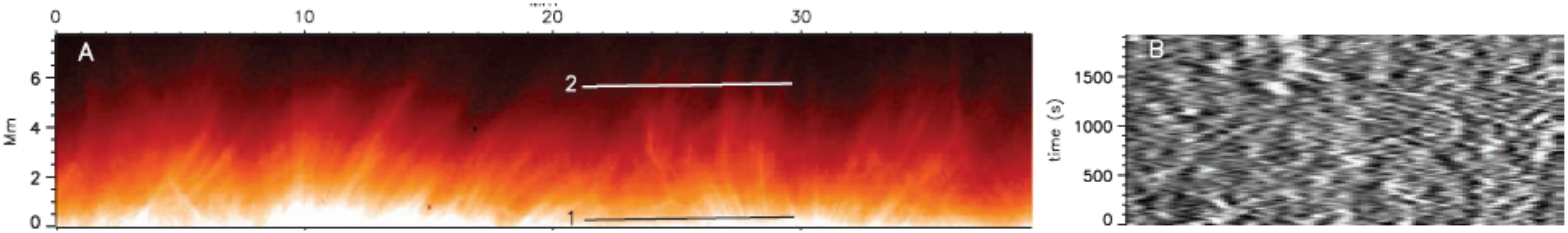
Overview

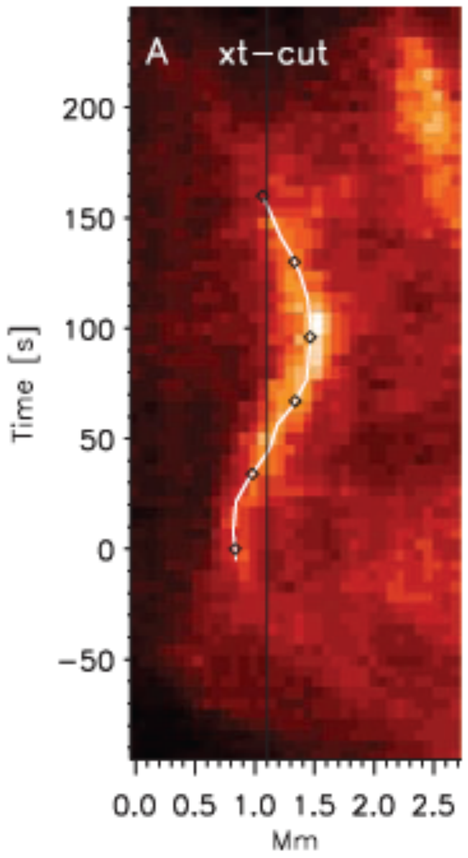
- Some recent **observations of [Alfvén(ic)] waves** in the chromosphere and corona
- Some thoughts on the **generation of [Alfvén(ic)] waves** in the solar atmosphere
- **Wave heating**
- **Mode coupling** to explain the observed damping of Doppler shift oscillations
- **Observational signatures** of wave heating

Alfvén(ic) Waves in the Chromosphere

De Pontieu et al (2007)

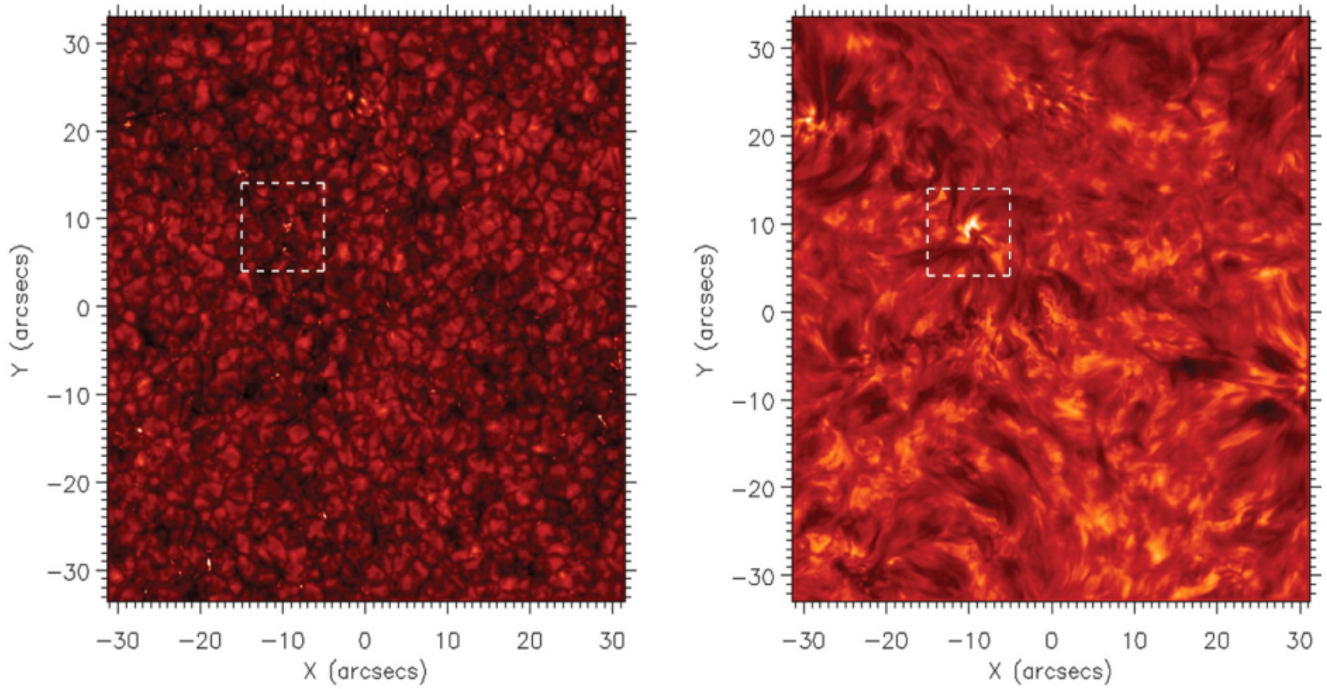


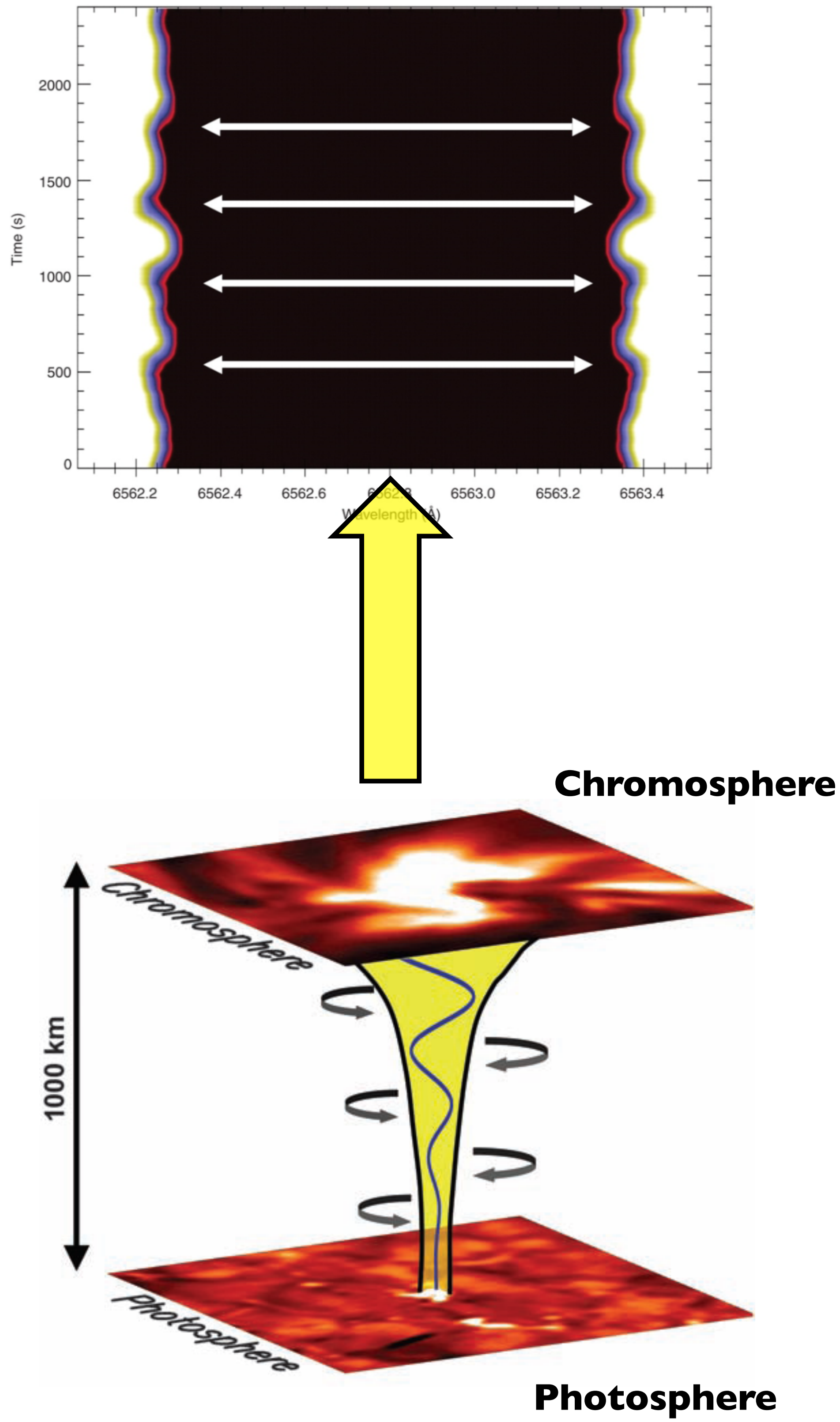
- “Swaying” spicules everywhere (Hinode/SOT)
  - Transverse motions ~ 500-1000km – comparable to width of spicules
  - Periods ~ few minutes – spicule lifetimes ~ 10-300 sec (mostly <100 sec)
  - Chromospheric energy flux ~ 4-7 kW m^{-2}
  - Coronal energy flux ~ 120 W m^{-2} (transmission coefficient ~ 3%)
  - Sufficient to heat the Quiet Sun corona and/or drive the solar wind (~100 W m^{-2})
  - Additional torsional motions reported by De Pontieu et al (2012)
    - Double energy budget?



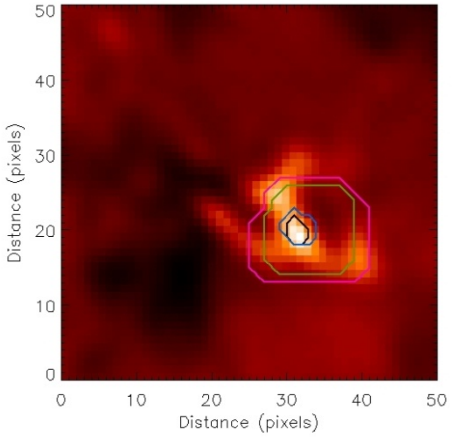
Alfvén(ic) Waves in the Chromosphere

Jess et al (2009)



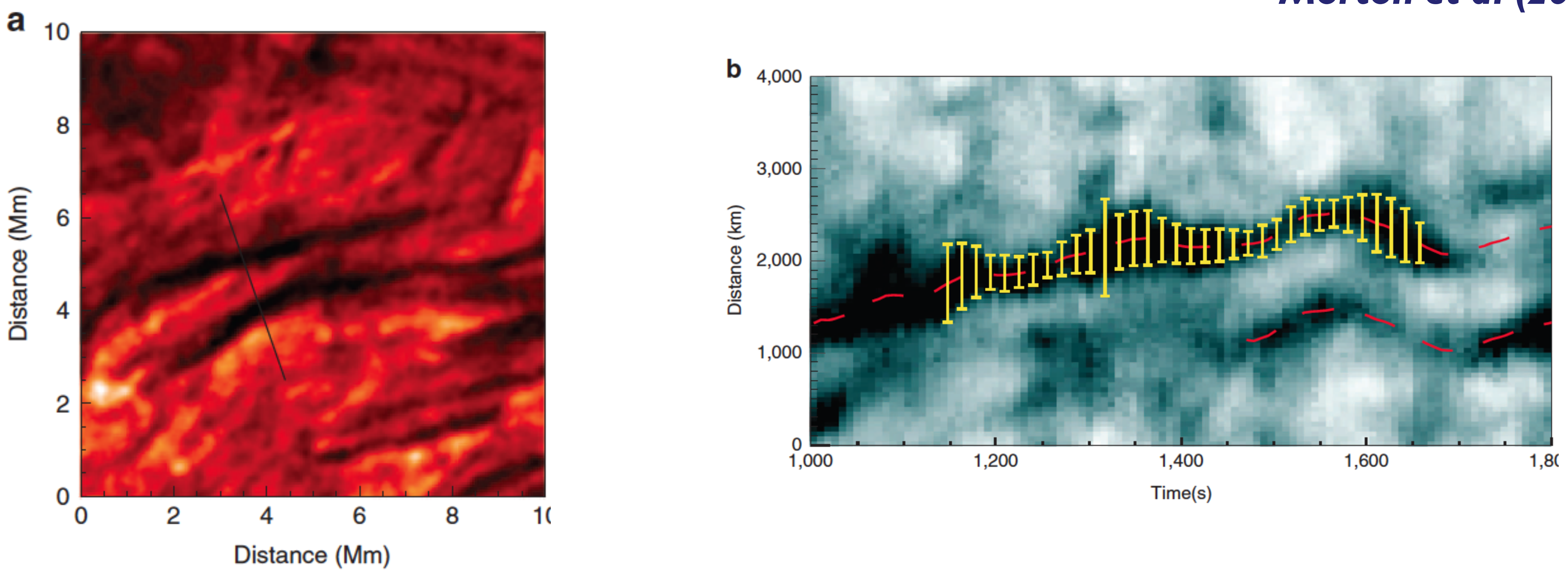


- ➢ Chromospheric bright point oscillations (SST)
- Periodic spectral line broadening; no intensity oscillations
  - Interpreted as torsional Alfvén waves
    - Frequency as a function of radius resolved
    - Chromospheric energy flux ~ 15,000 W m^{-2}
    - 1.6% of surface covered in Bright Points
      - Global average ~ 240 W m^{-2}
    - Transmission coefficient ~ 42%
      - Coronal energy flux ~ 100 W m^{-2}

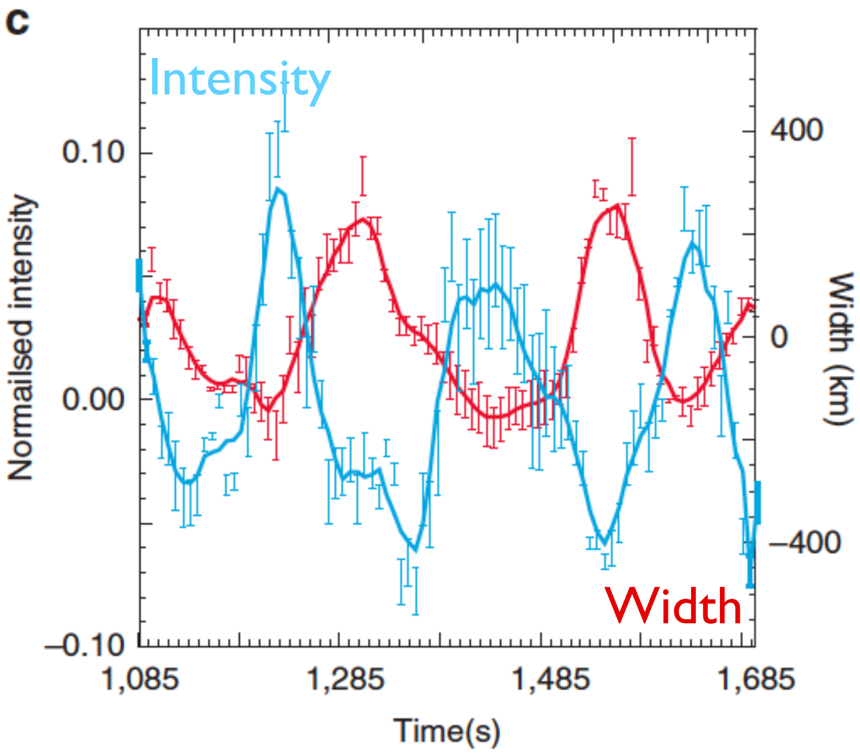


Compressive Waves in the Chromosphere

Morton et al (2012)

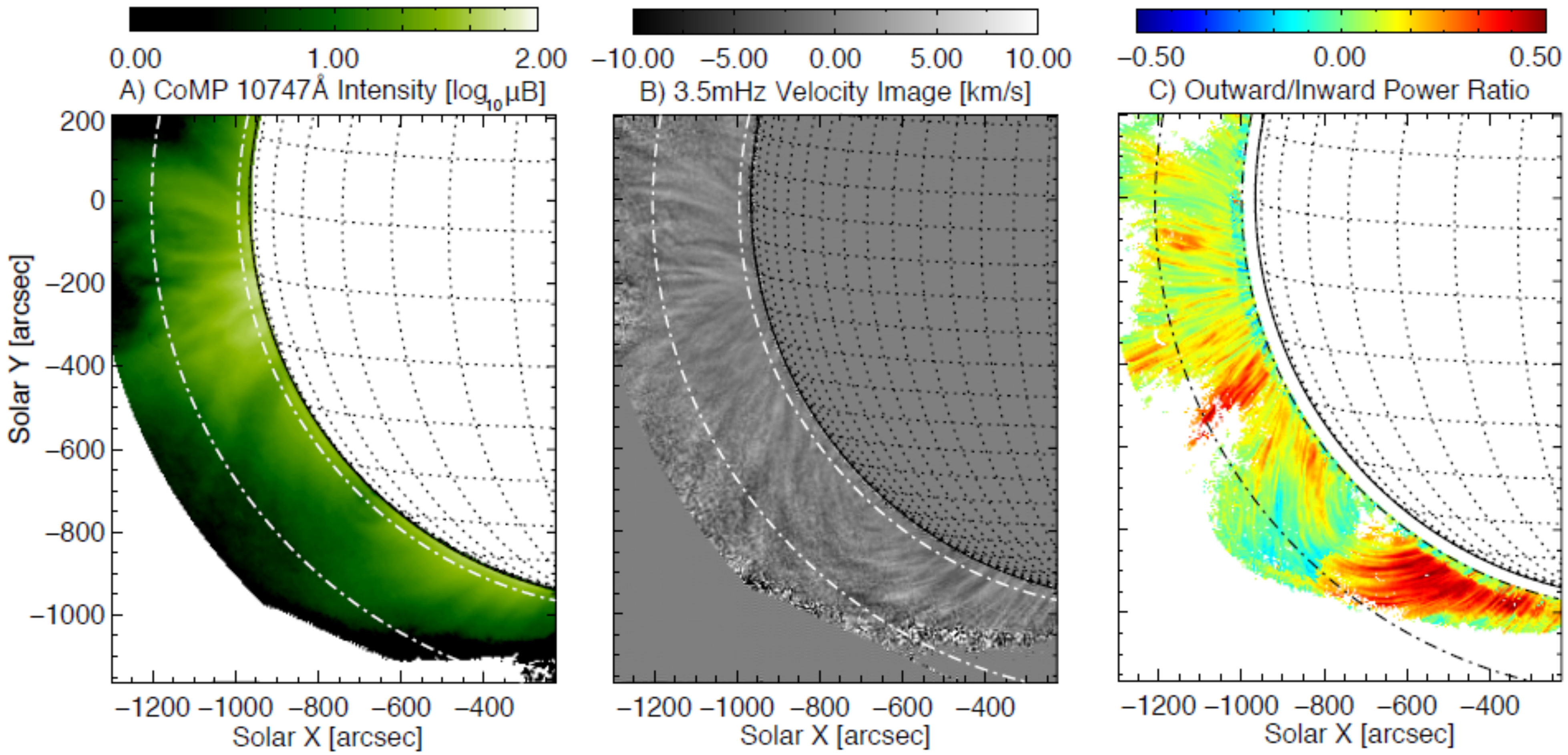


- Concurrent observations of (on disk) compressible and incompressible wave modes.
  - Transverse motions – fast kink wave
  - Periodic changes in intensity & cross section – fast MHD sausage mode
    - Incompressible energy ~ 4300 ± 2700 W m^{-2}
    - Compressible energy ~ 11700 ± 3800 W m^{-2}
  - Assume 4-5% connected to corona
    - Incompressible energy ~ 170 ± 110 W m^{-2}
    - Compressible energy ~ 460 ± 150 W m^{-2}



Alfvén(ic) Waves in the Corona

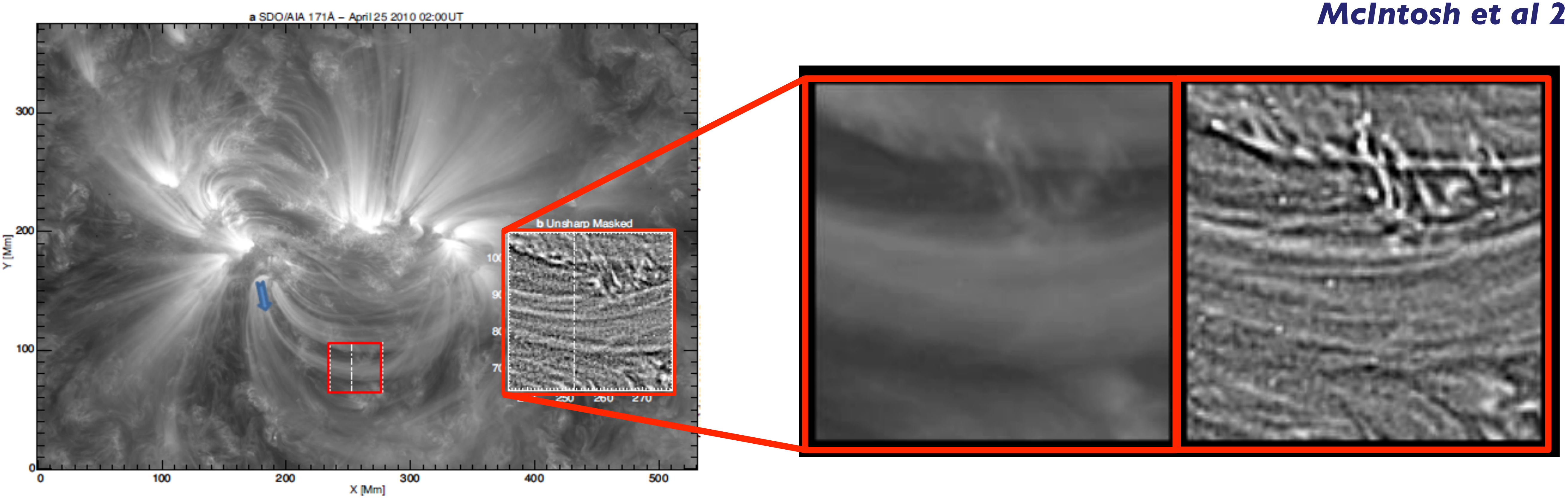
Tomczyk et al 2007; Tomczyk & McIntosh 2009



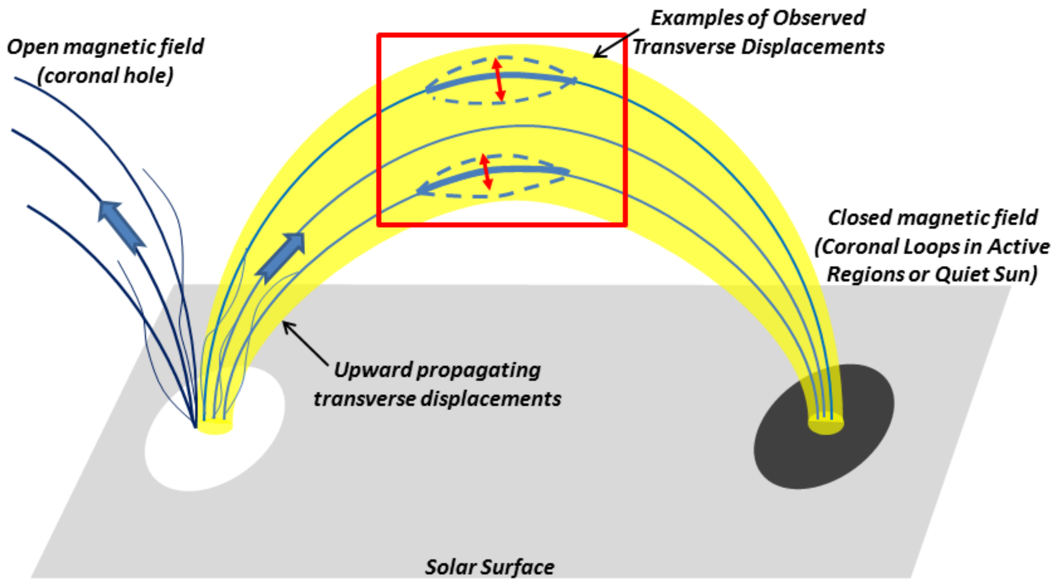
- ➢ Ubiquitous quasi-periodic fluctuations in velocity but no fluctuations in intensity
- Interpretation as propagating Alfvén waves based on high phase speeds (~ 1 Mm/s), field-aligned, and very small intensity fluctuations (incompressible)
- Disparity between outward and inward wave power (even along closed loops) suggests significant amplitude decay *in situ*
- Energy insufficient to account for heating?
  - F_W = 10–100 erg cm^{-2}s^{-1} vs 3 × 10^5 erg cm^{-2}s^{-1} needed for Quiet Sun

Alfvén(ic) Waves in the Corona

McIntosh et al 2011

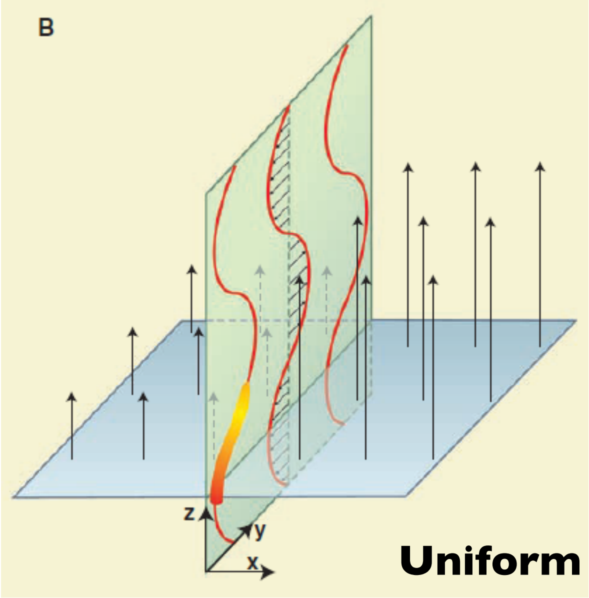


- Alfvénic motions everywhere (SDO/AIA)
  - Amplitudes ~ 5-20 km/s
  - Periods ~ 100 – 500 sec (lifetimes ~ 50-500 sec)
  - Energy flux Quiet Sun & Coronal Holes ~ 100 – 200 W m^{-2}
  - Active Region Loops ~ 100 W m^{-2} (2000 W m^{-2} needed)

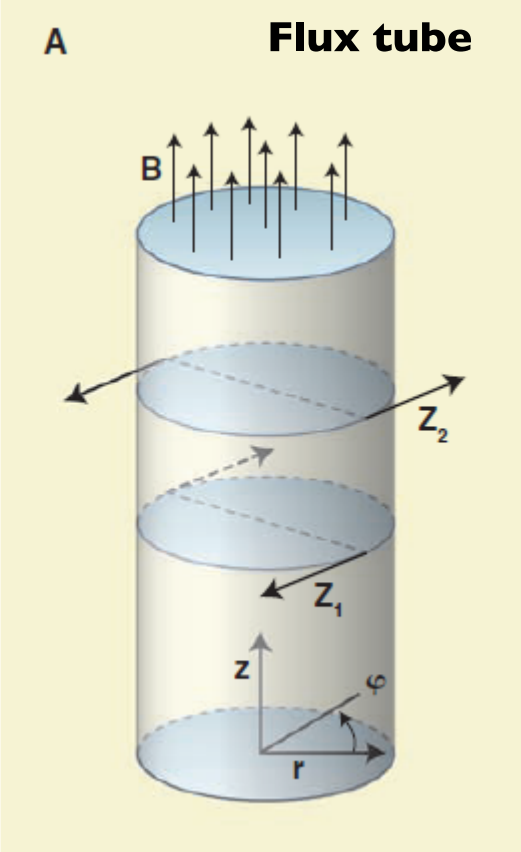


De Moortel & Pascoe 2012; McIntosh & De Pontieu 2012

Generation of Alfvén(ic) Waves



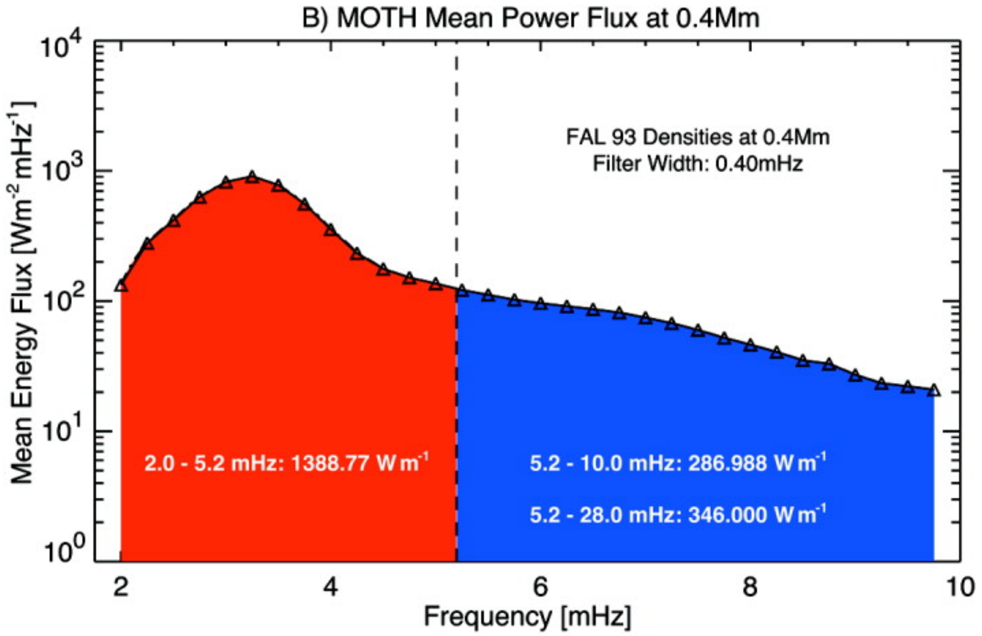
- How do these Alfvén(ic)/kink waves get there?
  - Flares, reconnection events and other disturbances can generate Alfvén waves.
  - With almost any kind of footpoint motion you will generate Alfvén waves.
    - Uniform: transverse motion → Shear Alfvén waves
    - Non-uniform: transverse motion → kink wave → mode coupling → (azimuthal) Alfvén wave
    - Non-uniform: vortex motion →Torsional Alfvén wave
- Cut-off frequency? Yes *(but observed in the chromosphere/corona)*
- Reflection & Transmission? Yes *(but observed in the chromosphere/corona)*
- All of the above apply largely to plane-parallel and static atmosphere.
- What happens if the ‘flux tubes’ are continuously evolving?
  - Is there such a thing as a ‘stable’ wave guide?
  - Do we need them?



Erdelyi & Fedun 2007

Long Periods?

- Many of the frequencies observed in the atmosphere are below the 'traditional' cut-off frequency.
  - Inclination of the field lines 'reduces' the effect of gravity – increase cut-off frequency *(e.g.Bel & Leroy 1977; De Pontieu et al 2005)*
  - Energy flux of observed low-freq (<5 mHz) >> high-freq waves *(see also Fossum & Carlsson 2005, 2006; Carlsson et al 2007)*



Jefferies et al 2006

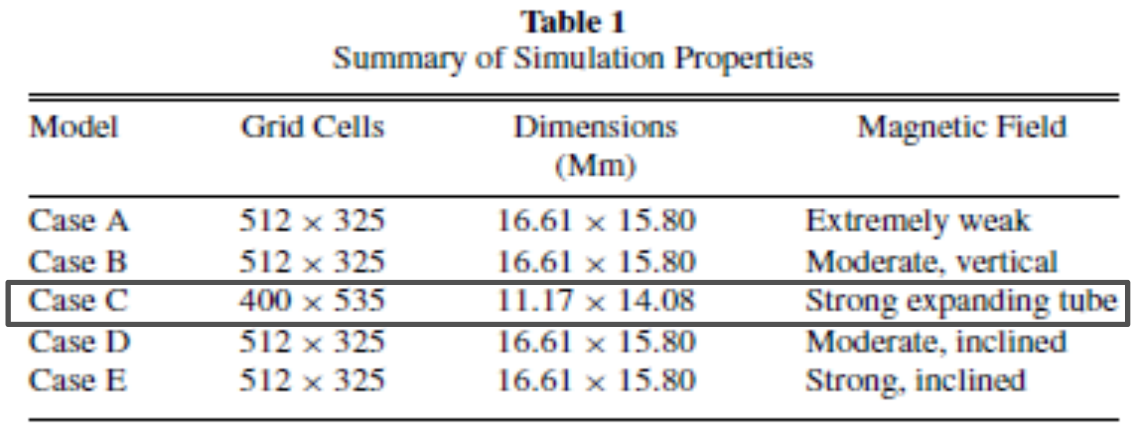
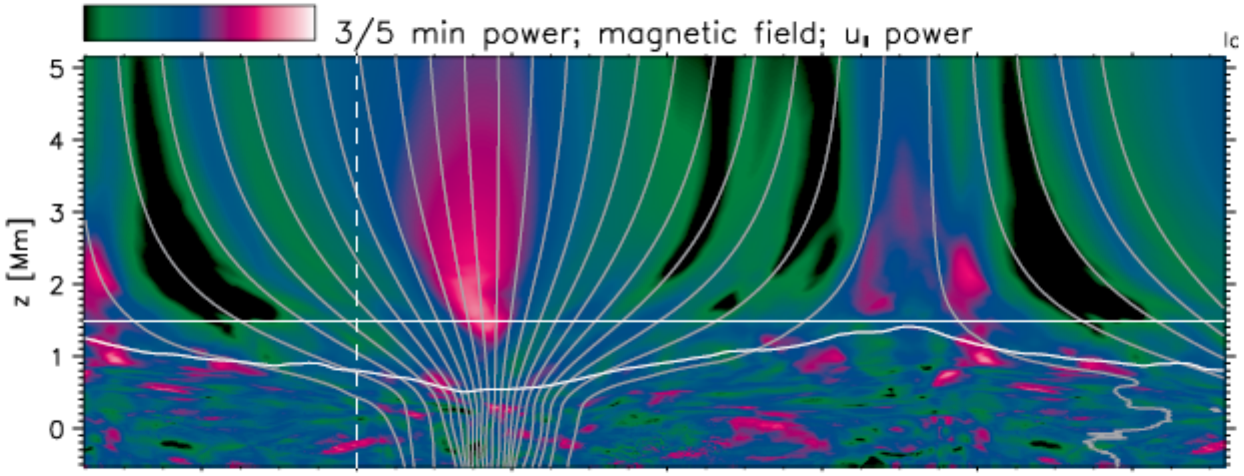


Table 1
Summary of Simulation Properties

Model	Grid Cells	Dimensions (Mm)	Magnetic Field
Case A	512 × 325	16.61 × 15.80	Extremely weak
Case B	512 × 325	16.61 × 15.80	Moderate, vertical
Case C	400 × 535	11.17 × 14.08	Strong expanding tube
Case D	512 × 325	16.61 × 15.80	Moderate, inclined
Case E	512 × 325	16.61 × 15.80	Strong, inclined

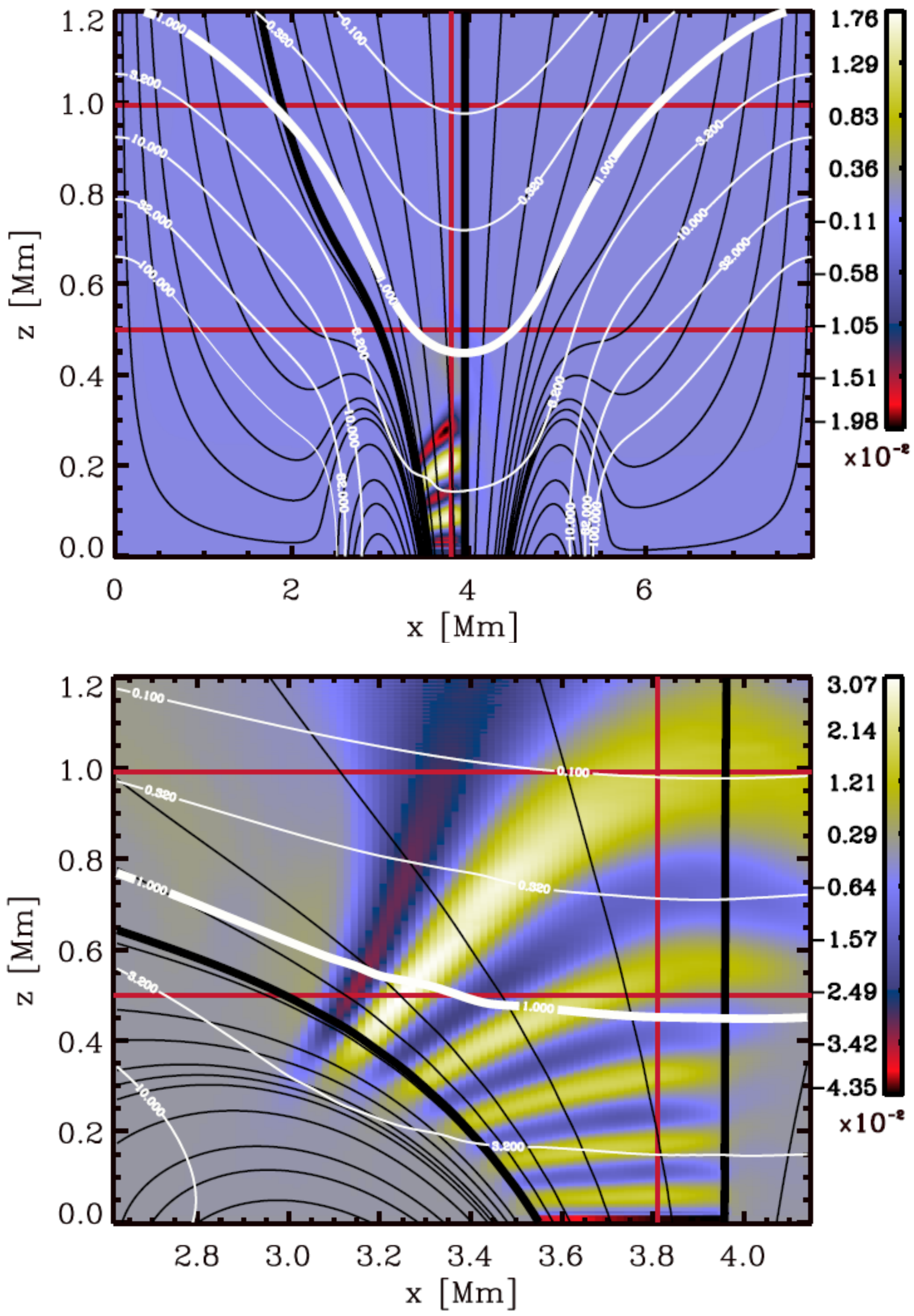
Heggland et al 2011



- *Heggland et al (2011):* Numerical simulations driven self-consistently (i.e. no harmonic driving imposed)
  - Long-period propagation: dominated by inclination, not changes in radiative relaxation time
    - Strong, inclined field: 5 mins
    - Weak or vertical field: 3 mins
    - Atmospheric conditions also change on timescale of minutes…

Bel & Leroy 1977; Fontenla et al 1993; De Pontieu et al 2005; McIntosh & Jefferies 2006; Jefferies et al 2006; Bloomfield et al 2006; Erdelyi et al 2007; Vecchio et al 2007; Heggland et al 2011;…

Footpoint Motions

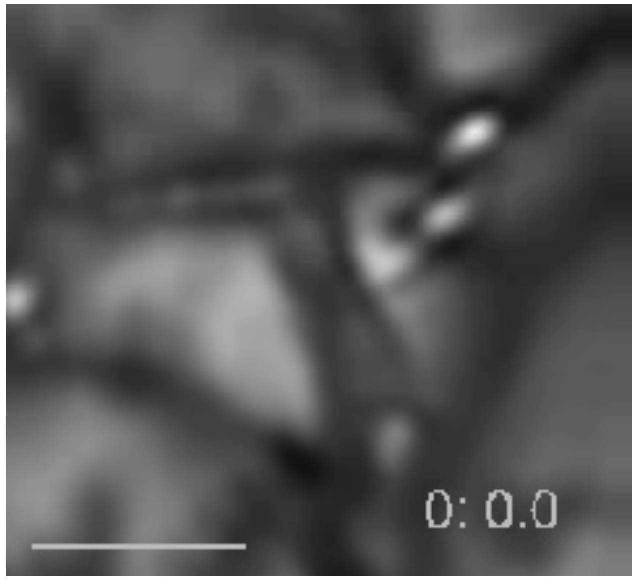


- Convection will generate a large number of different waves:
  - — fast, slow, shear Alfvén,
  - — kink & sausage fast and slow, torsional Alfvén
  - ‘Wave’ flux at top of convection zone ~ 10^7 erg cm^{-2} s^{-1} *(Narain & Ulmschneider 1996)*
  - Reflection of Chromosphere and Transition Region
  - Mode coupling (β=1)
- Footpoint motions can “get through”, i.e. some fraction of energy will be transmitted into the corona
- Probably not a straightforward or one-to-one correspondence between footpoint motions and observed coronal ‘motions’ (waves).
- Identifying driver and tracking through the atmosphere?

Hollweg 1981, 1984,1985; Ionson 1982; Stein & Nordlund 1991; Rosenthal et al 2002; Bogdan et al 2003; Carlsson & Bogdan 2006;...

Vortex Driving Motions

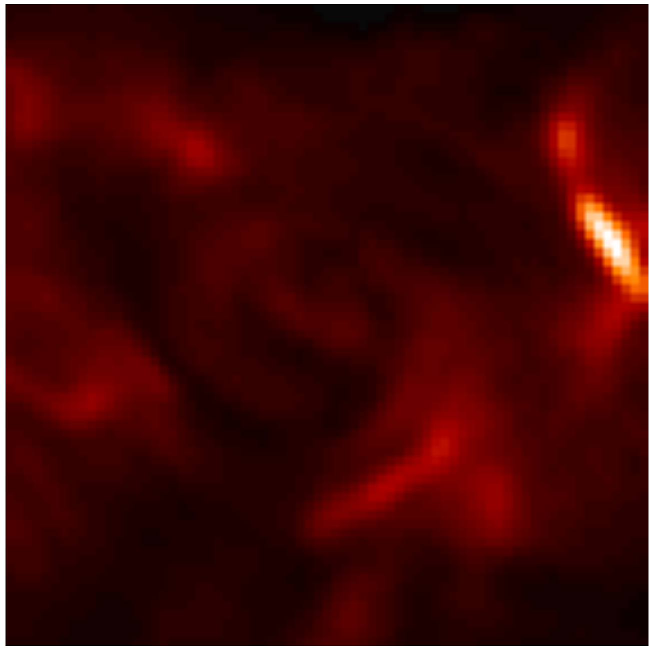
Photospheric G-band movie



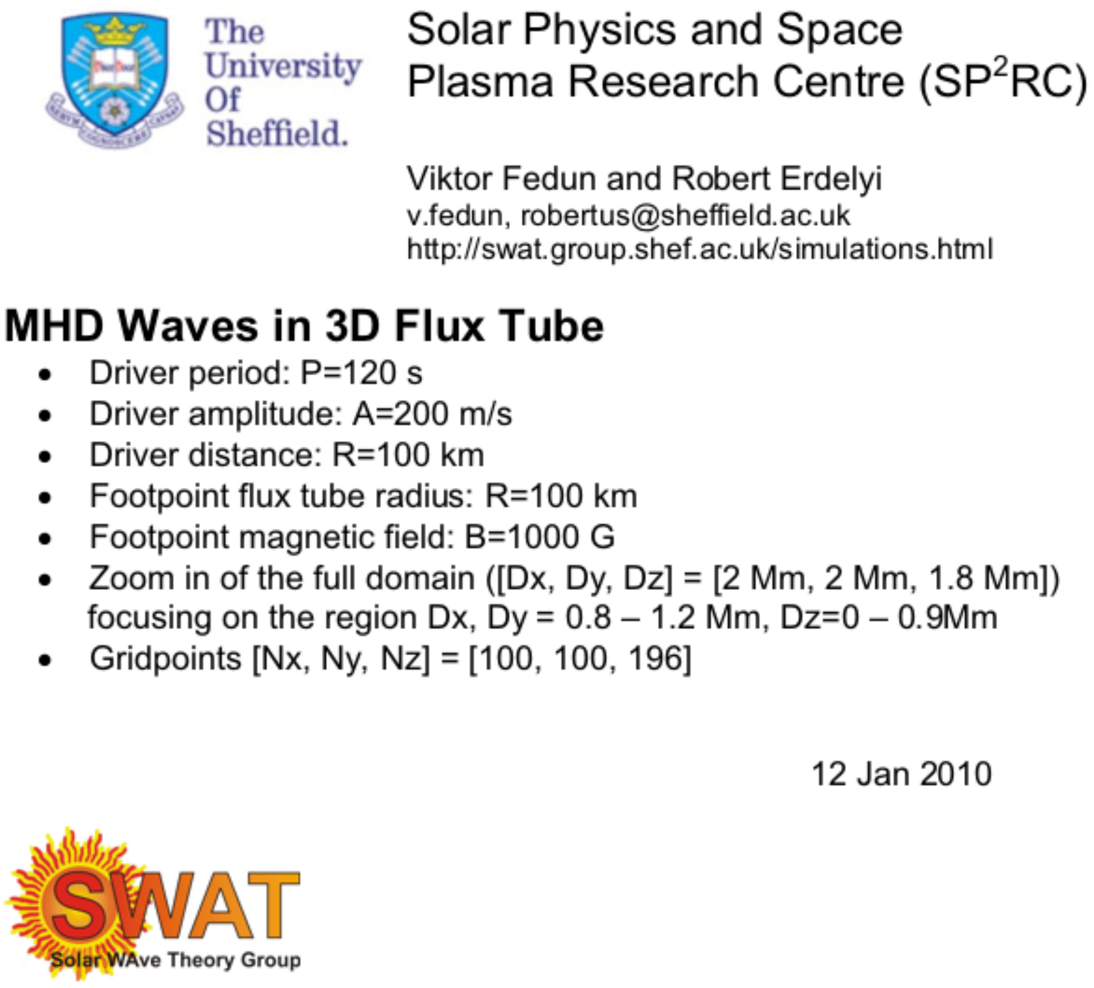
Bonet et al 2008

- Simulations show that convection naturally leads to vortex motions of magnetic flux elements *(Vogler et al. 2005; Carlsson et al. 2010; Shelyag et al. 2010)*
- *Bonet et al (2008):* SST observations of magnetic bright points show vortex motions (lifetimes ~ 5 mins)
  - ➢ **Torsional Alfvén waves generated all over photosphere?**

Chromospheric Ca II movie



Wedemeyer-Bhöm & Rouppe van der Voort (2009)



The University Of Sheffield.

Solar Physics and Space Plasma Research Centre (SP^{2}RC)

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http://swat.group.shef.ac.uk/simulations.html

MHD Waves in 3D Flux Tube

- Driver period: P=120 s
- Driver amplitude: A=200 m/s
- Driver distance: R=100 km
- Footpoint flux tube radius: R=100 km
- Footpoint magnetic field: B=1000 G
- Zoom in of the full domain ([Dx, Dy, Dz] = [2 Mm, 2 Mm, 1.8 Mm]) focusing on the region Dx, Dy = 0.8 – 1.2 Mm, Dz=0 – 0.9Mm
- Gridpoints [Nx, Ny, Nz] = [100, 100, 196]

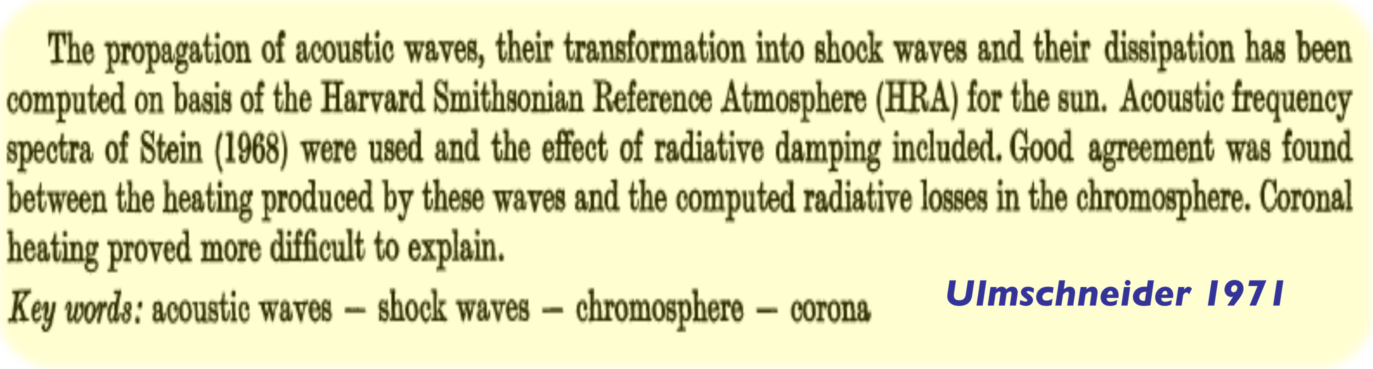
12 Jan 2010

SWAT
Solar WAve Theory Group

Fedun & Erdélyi 2011; Erdélyi et al 2011

Wave Heating

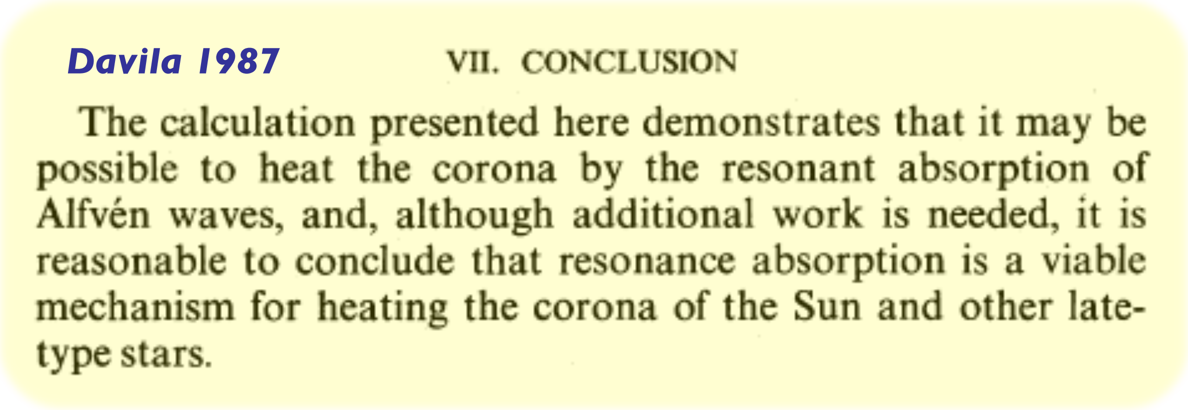
- Historically first suggested as heating mechanism *(Biermann 1946, 1948; Schwarzchild 1948)*
- (Some) Alfven waves not reflected at chromosphere *(Hollweg 1978,1984,1985)* and hence could heat corona *(Wentzel 1974, 1976)*
  - Resonant absorption *(Ionson 1978; Goossens 2011)*
  - Phase mixing *(Heyvaerts & Priest 1983)*
- ***Vast literature…***



The propagation of acoustic waves, their transformation into shock waves and their dissipation has been computed on basis of the Harvard Smithsonian Reference Atmosphere (HRA) for the sun. Acoustic frequency spectra of Stein (1968) were used and the effect of radiative damping included. Good agreement was found between the heating produced by these waves and the computed radiative losses in the chromosphere. Coronal heating proved more difficult to explain.

Key words: acoustic waves – shock waves – chromosphere – corona

Ulmschneider 1971



Davila 1987

VII. CONCLUSION

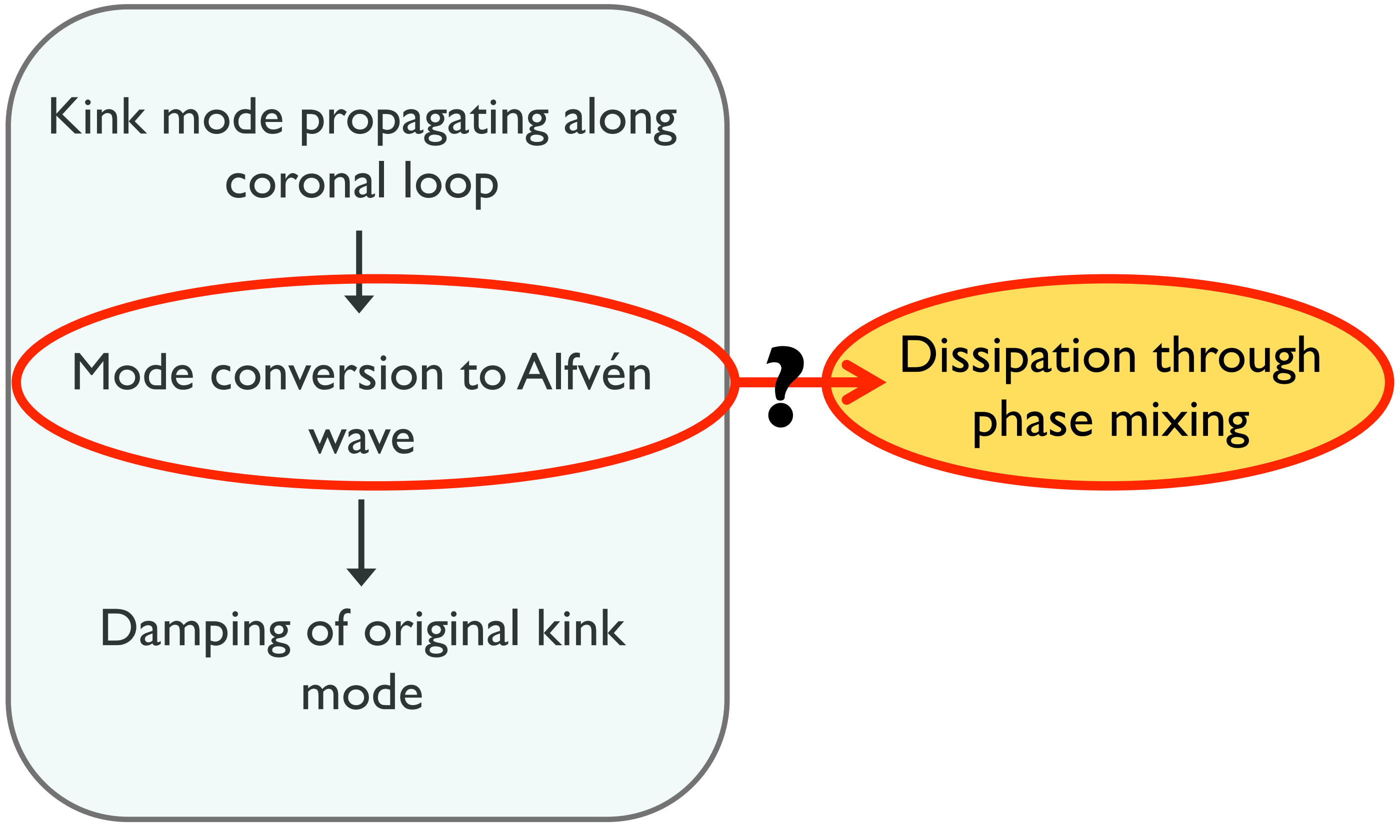
The calculation presented here demonstrates that it may be possible to heat the corona by the resonant absorption of Alfvén waves, and, although additional work is needed, it is reasonable to conclude that resonance absorption is a viable mechanism for heating the corona of the Sun and other late-type stars.

➢ **In the context of the recent observations:**

- Sufficient flux ≠ (right) heating
- Damping ≠ Dissipation *(e.g. Lee & Roberts 1986)*

- Timing? (dissipation time >> damping time?)

Talk Inigo Arregui (?)



Kink mode propagating along coronal loop

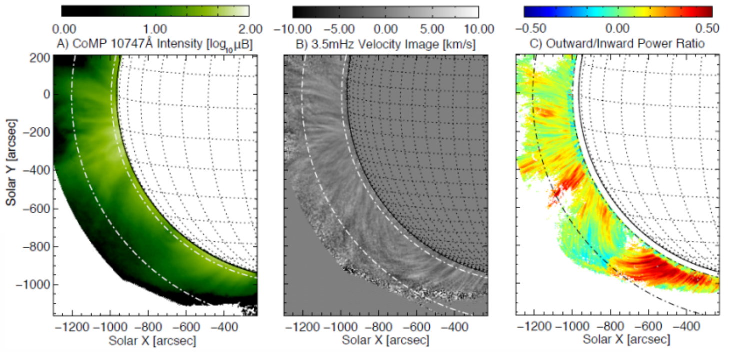
Mode conversion to Alfvén wave

Damping of original kink mode

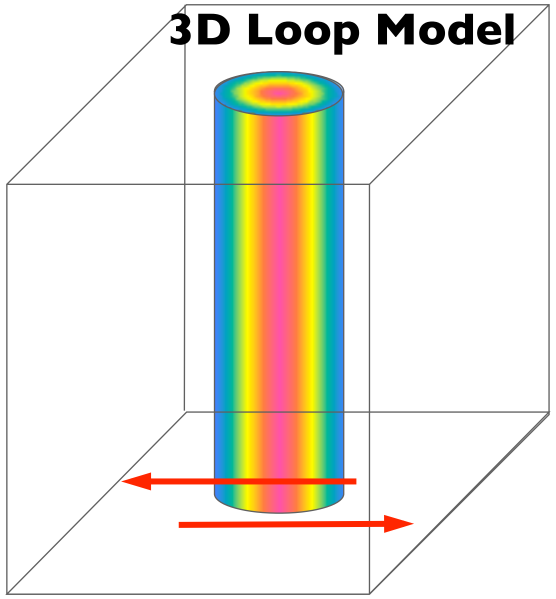
?

Dissipation through phase mixing

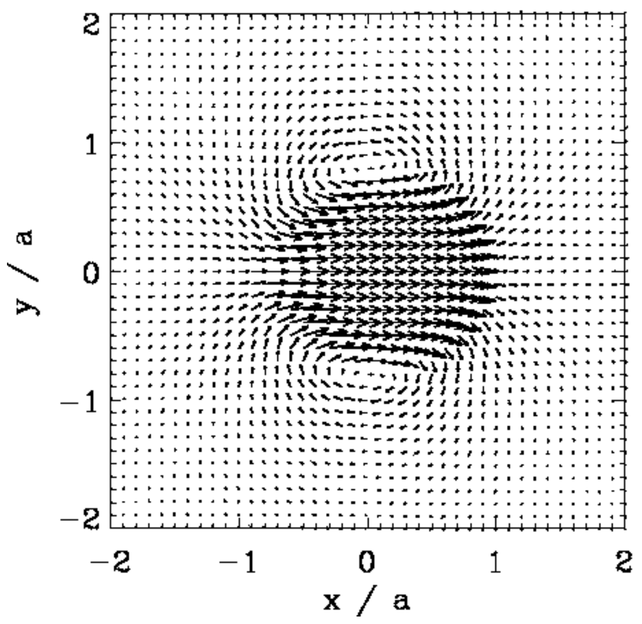
Mode Coupling

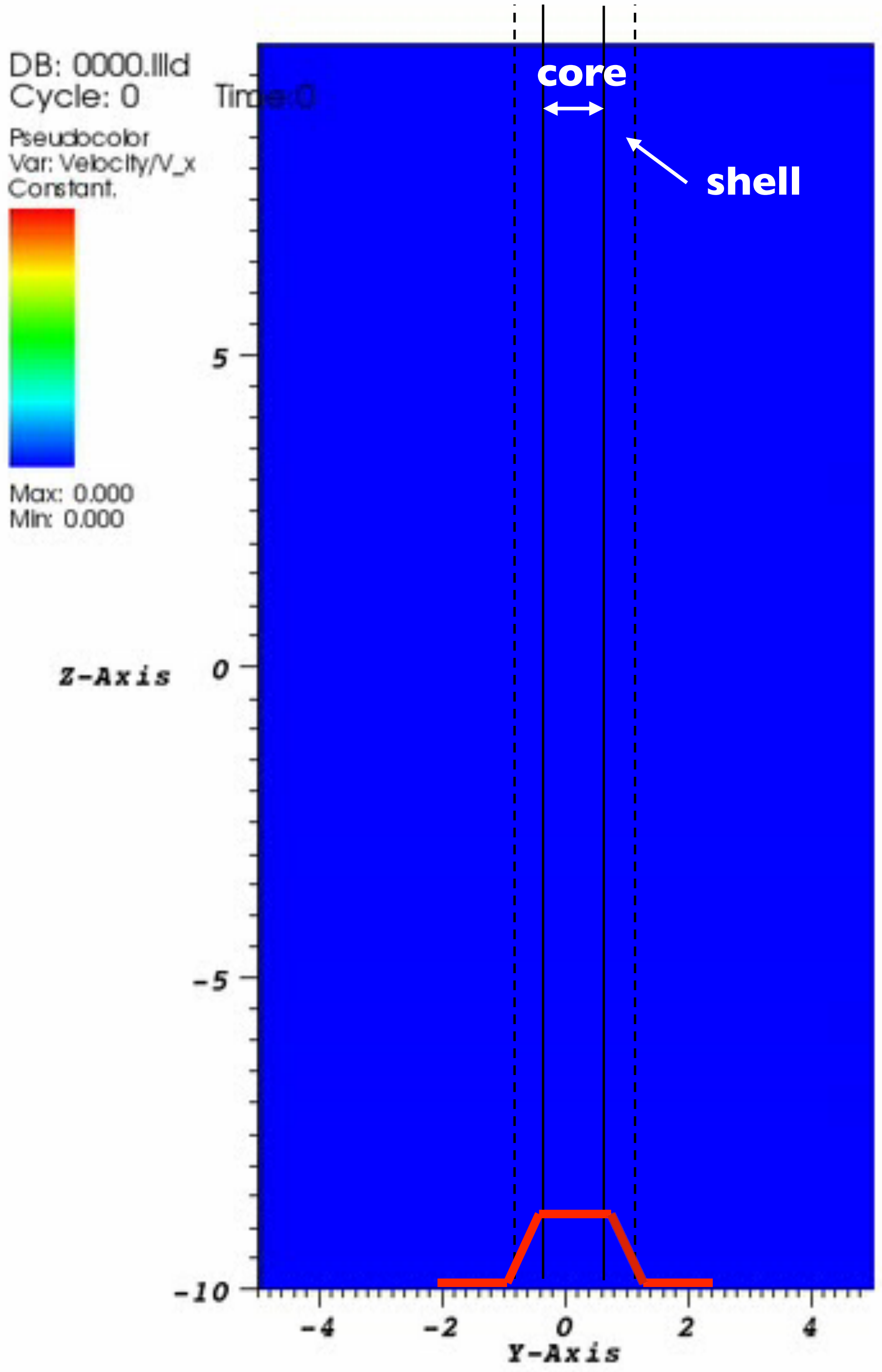


Pascoe et al 2010



Driver: models buffeting by solar surface motions





Kink mode propagating along coronal loop

↓

Mode conversion to Alfvén wave

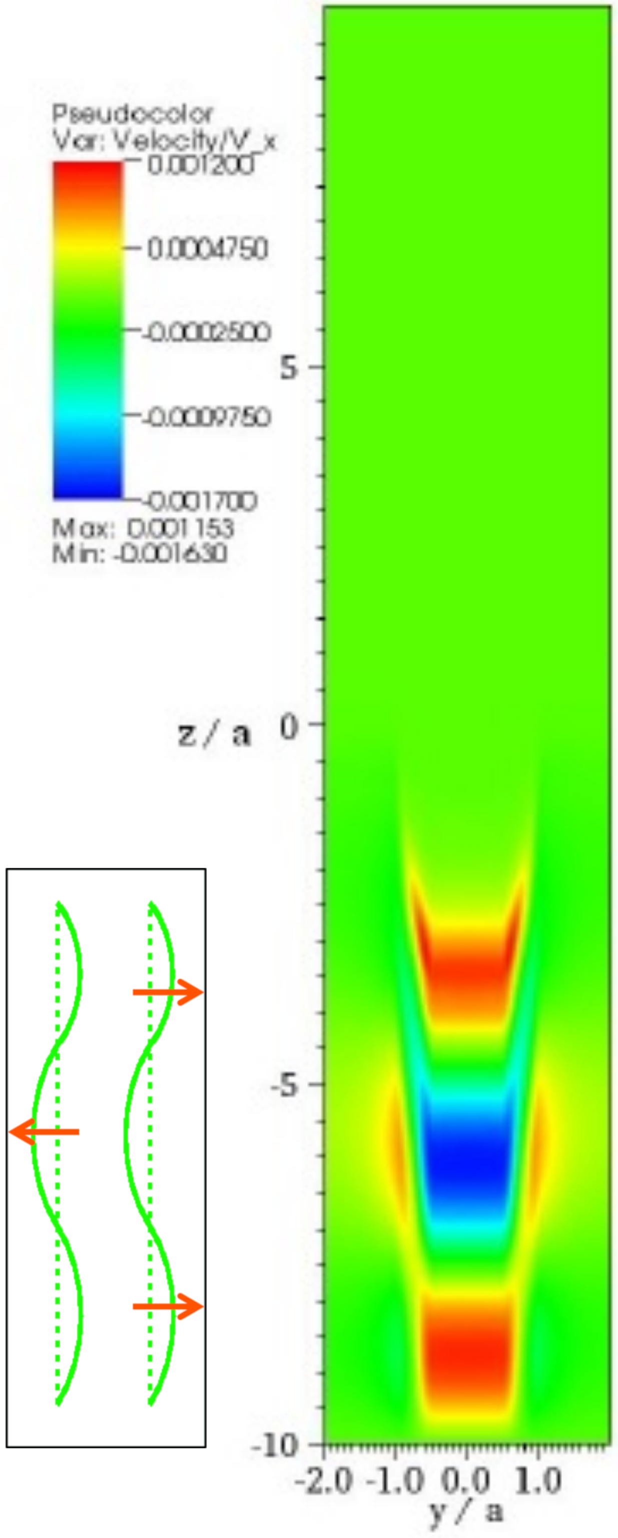
↓

Damping of original kink mode

user: dpascoe
Wed Dec 3 23:25:29 2008

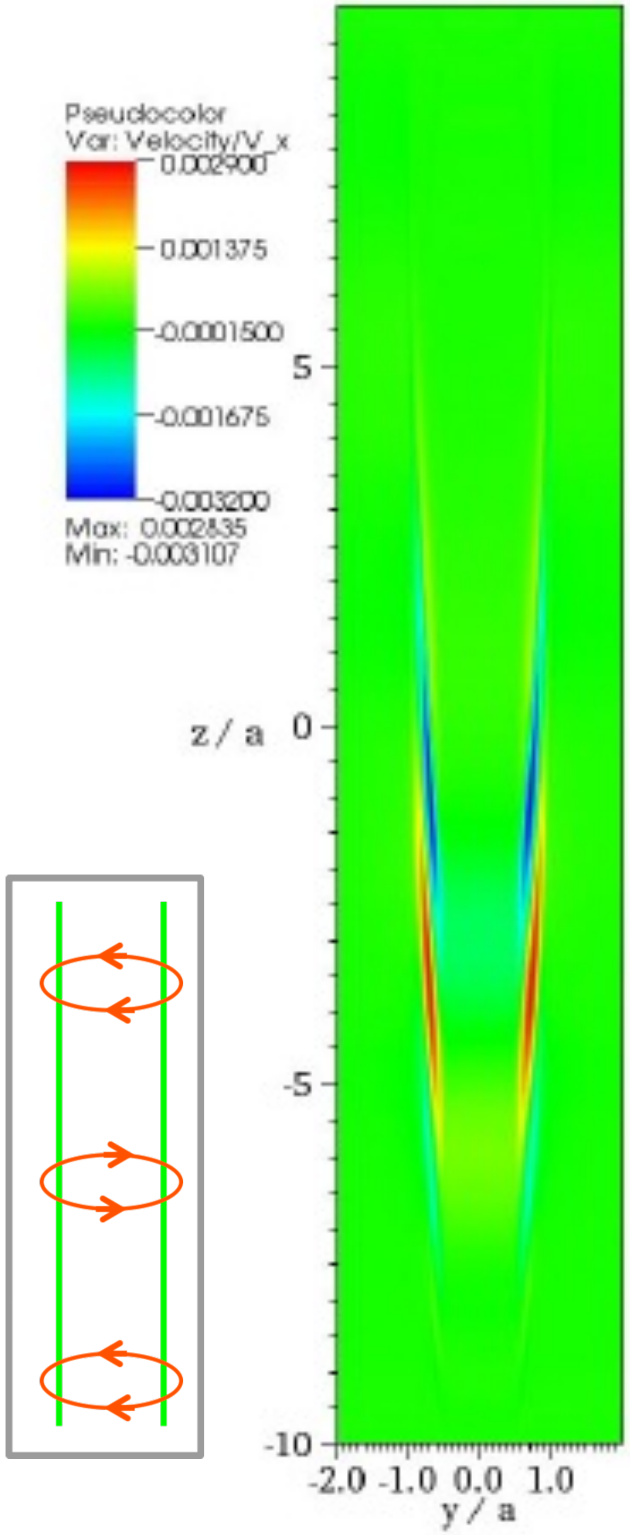
Coupled (*Alfvénic*) Mode

Kink

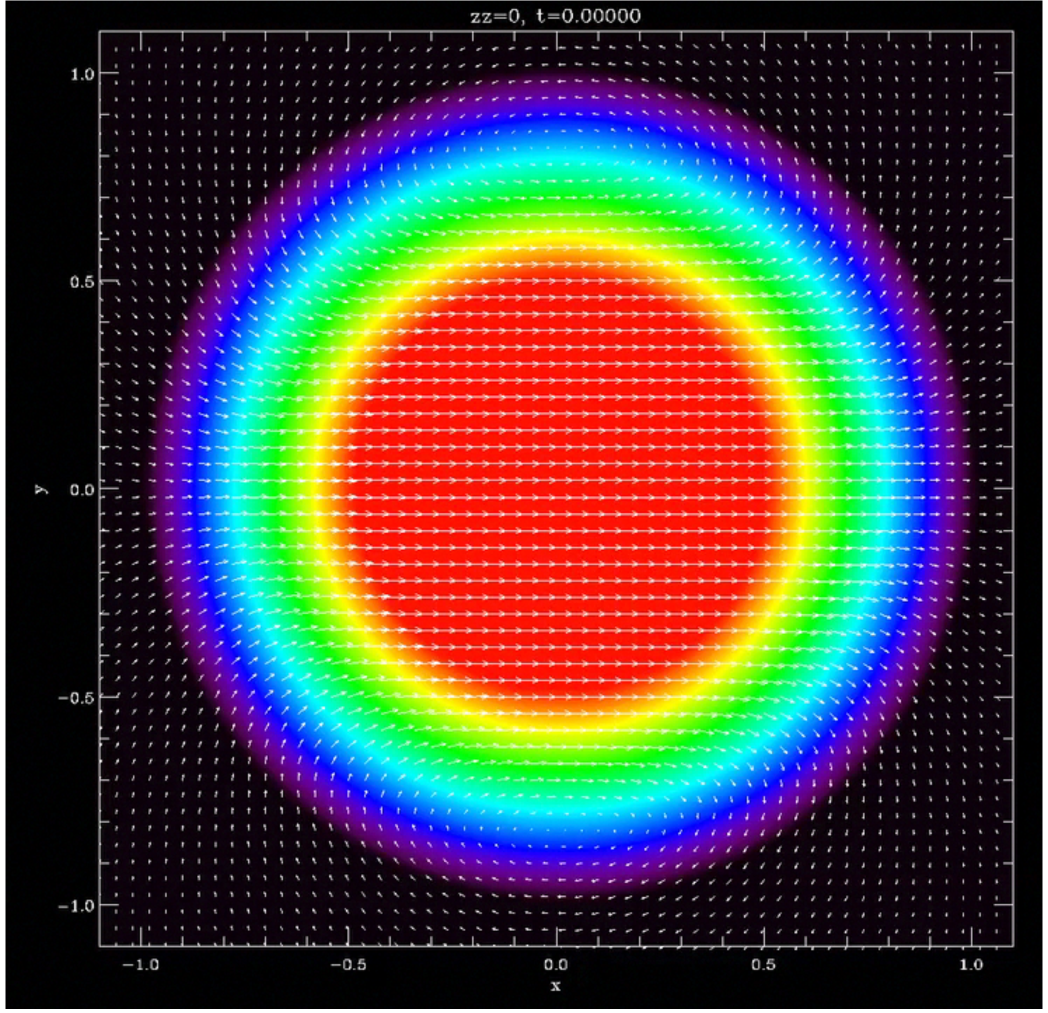


$t = P_0$

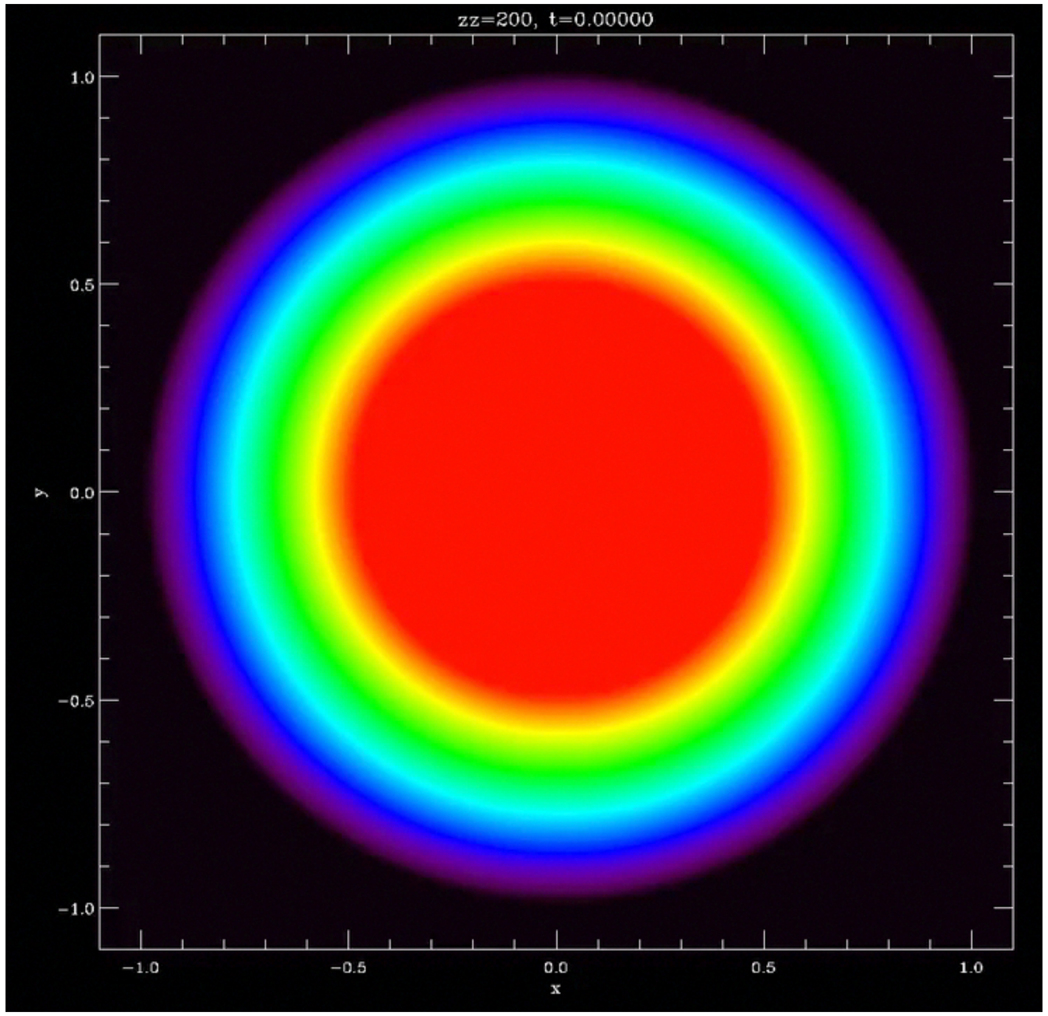
Alfvén (m=1)



$t = 5P_0$

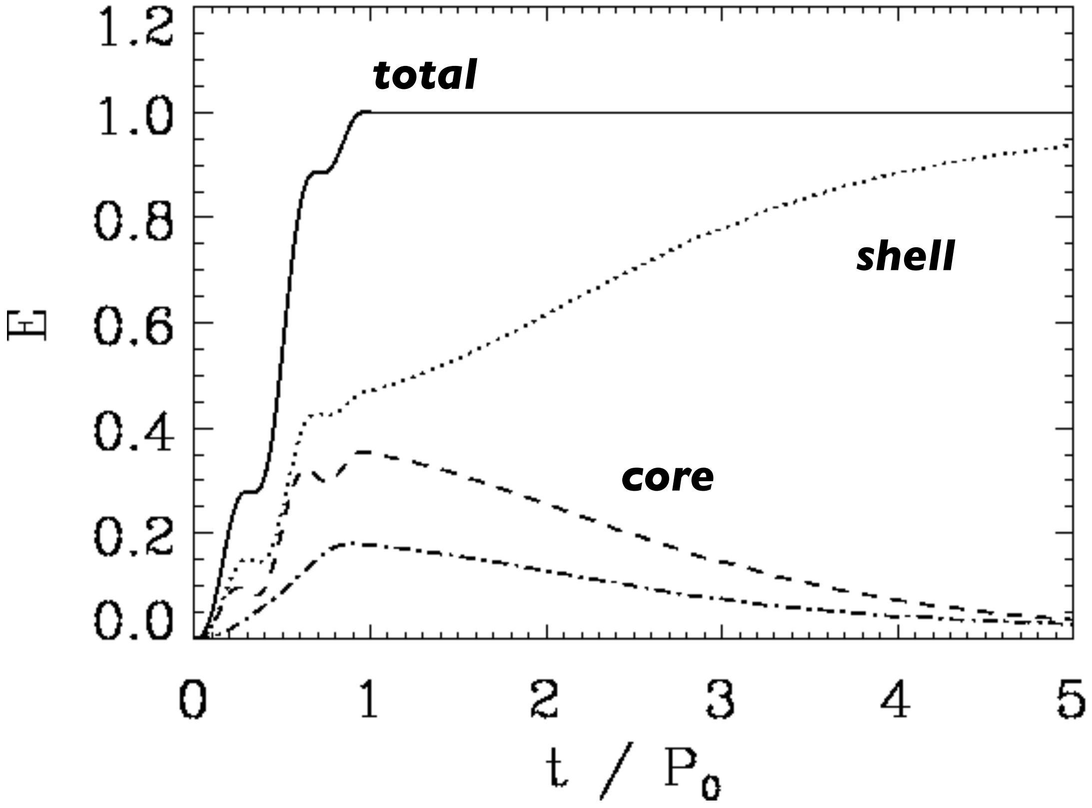


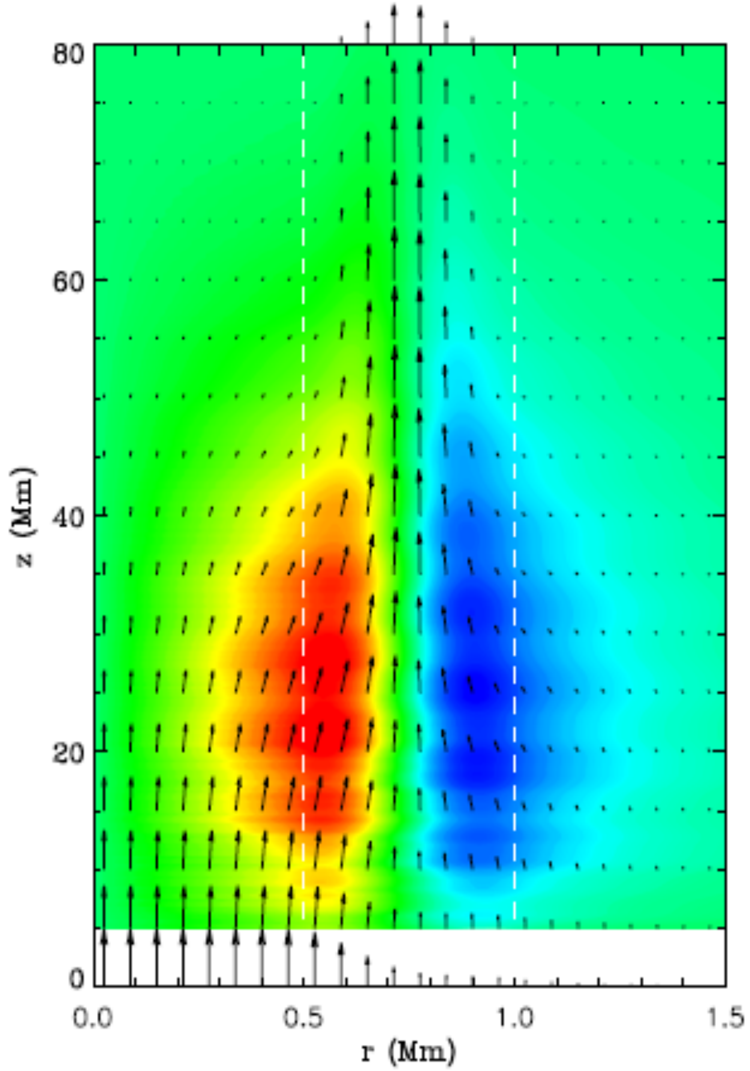
Z=0



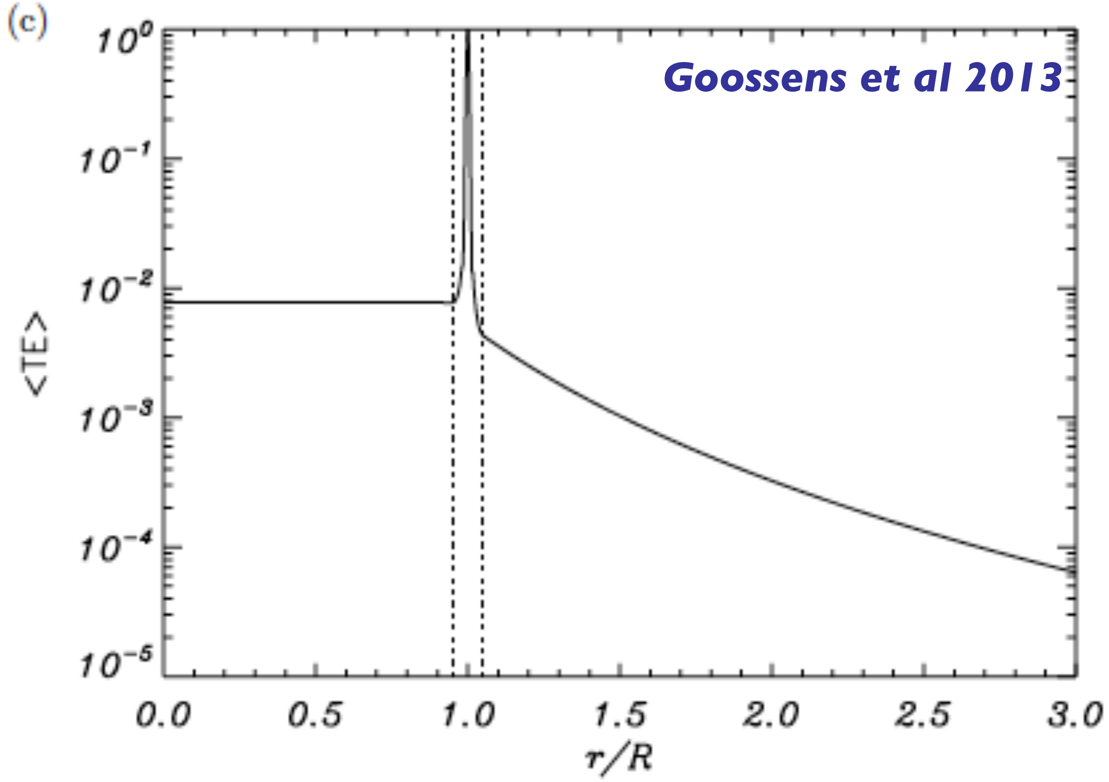
Z=200

Wave Energy





- Wave energy becomes increasingly localised in tube boundary.
- Damping in qualitative agreement with CoMP observations
  - ➢ **Damping ≠ Dissipation!**

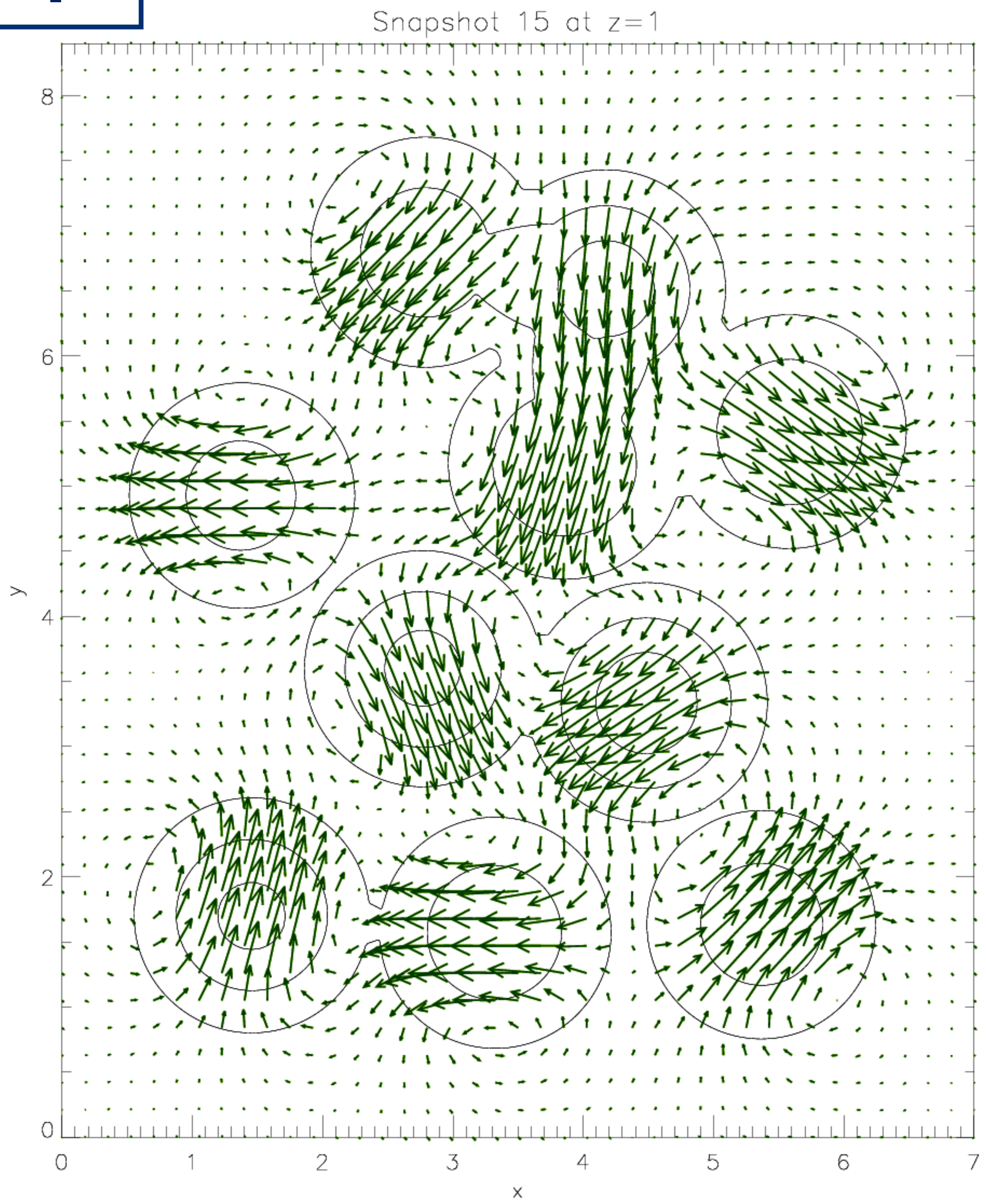


Goossens et al 2013

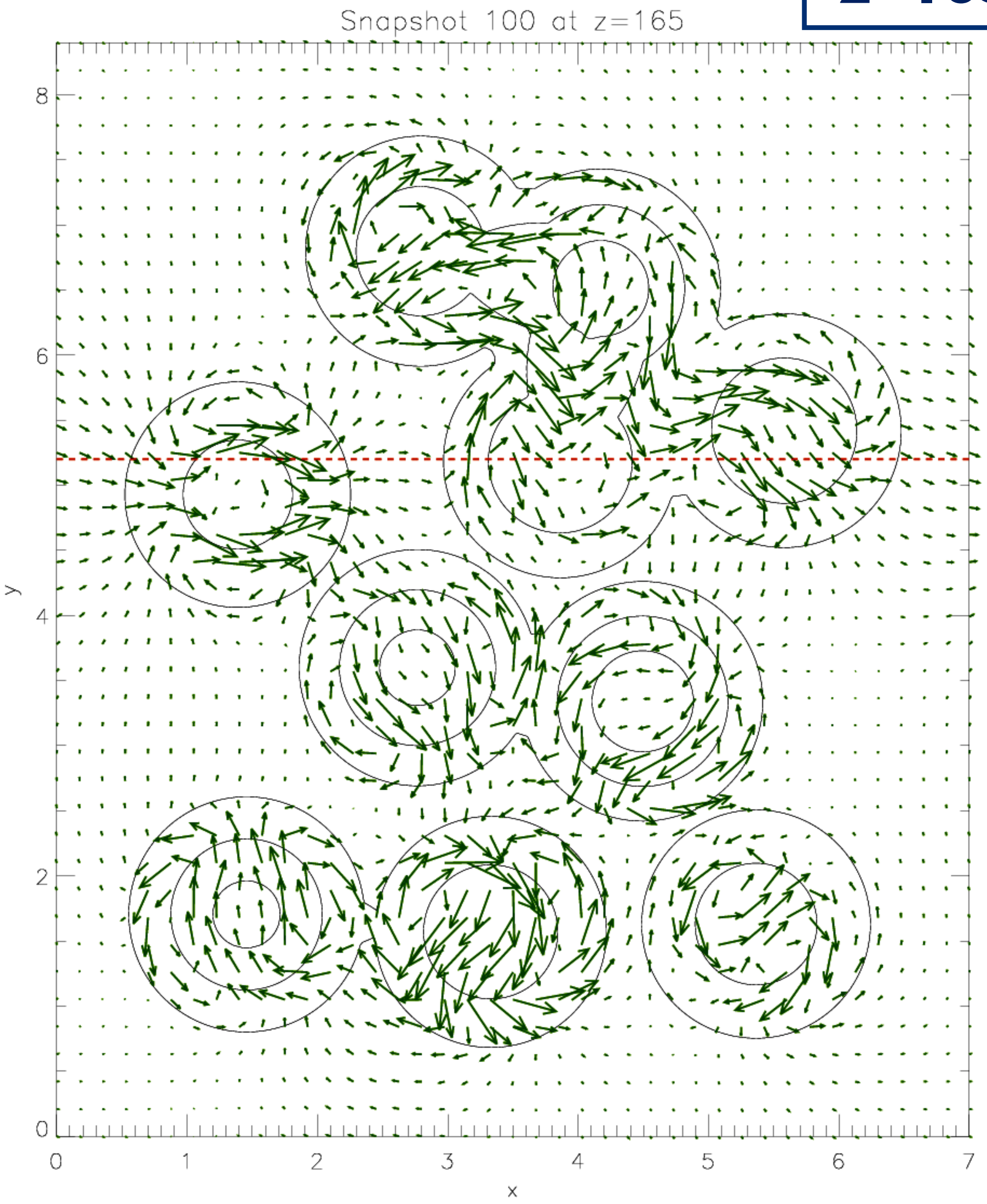
Pascoe et al 2010 - 2013; Terradas et al 2010; Verth et al 2010; Soler et al 2011a,b,c; Hood et al 2013; Goossens et al 2013

What if there was more than 1 loop in the corona?

z=1

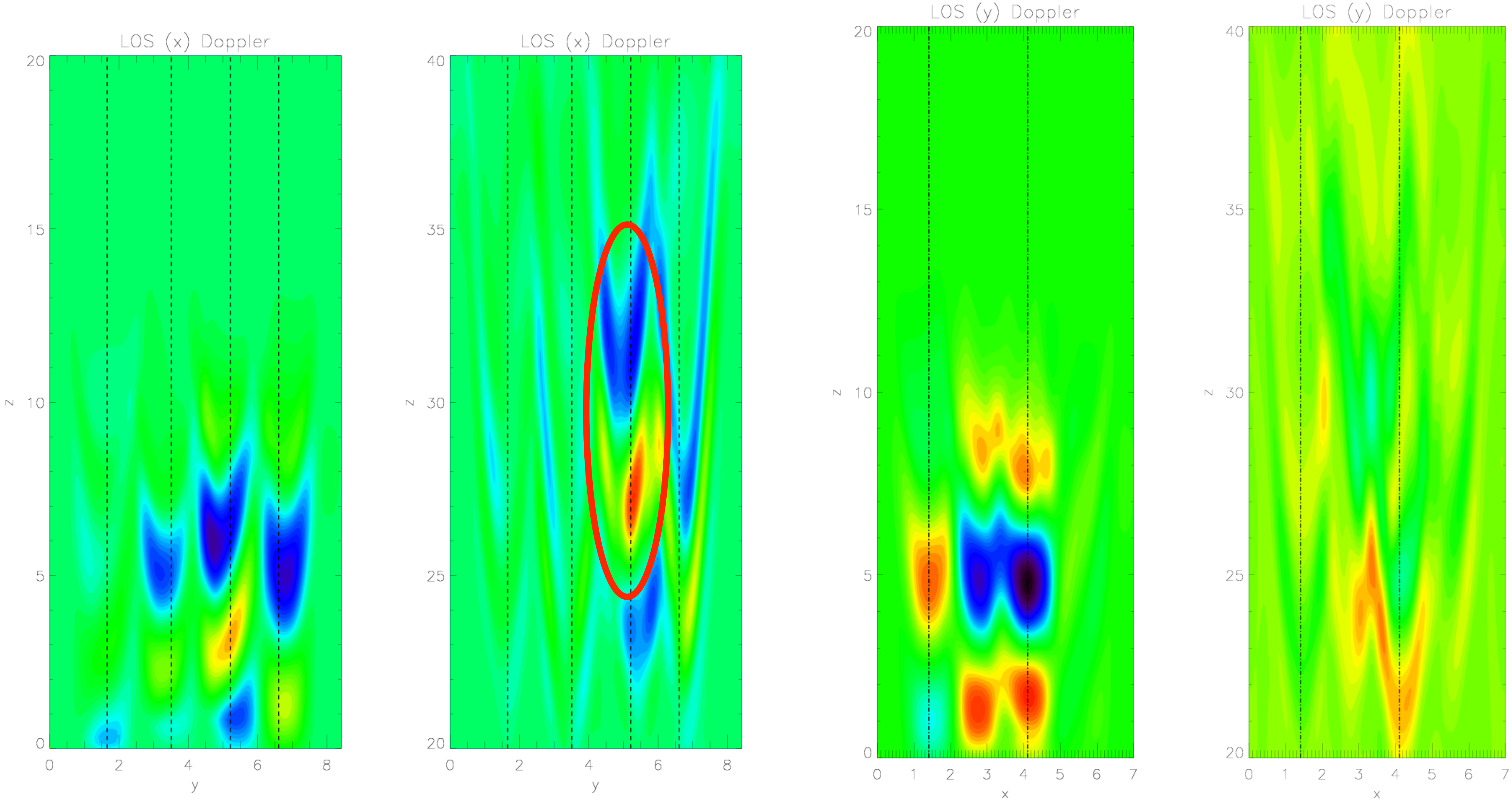


z=165



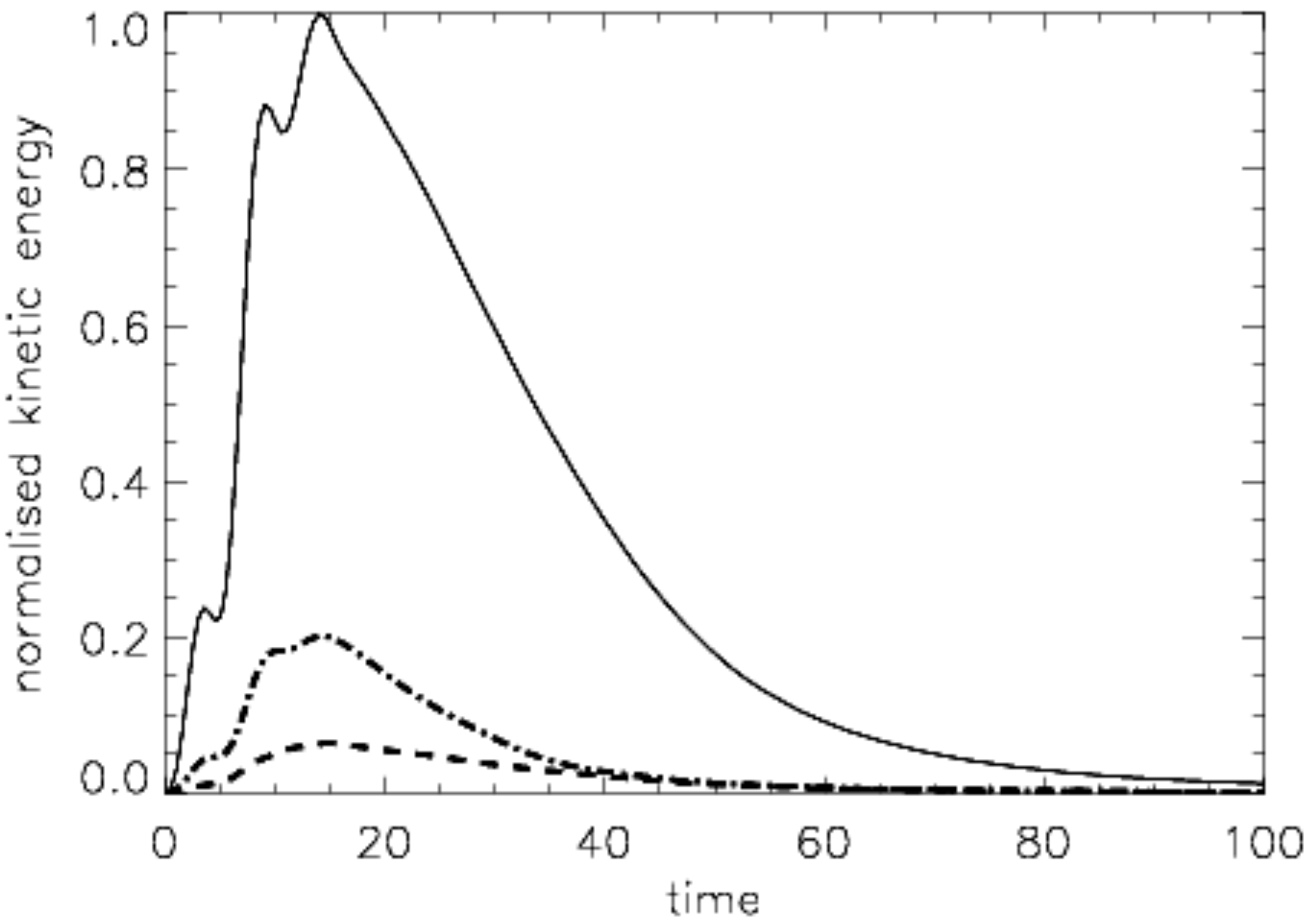
- Randomly directed driver clearly visible at bottom boundary
- Loops have different density contrasts and driver periods:
  - Mixture of azimuthal Alfven waves and transverse (Alfvenic/kink) modes at higher height

LOS integrated velocities (Doppler)



- Driven kink mode generally corresponds to bulk motion (periodic Doppler shifts) but cannot tell with which loops the oscillations are associated
- Doppler velocities much smaller than actual perturbations in domain
- y-LOS: strong oscillation which does not line up with a loop
- Alfven wave (m=1) appears as bulk motion in some locations (but very low amplitude in this simulation)

LOS Energy



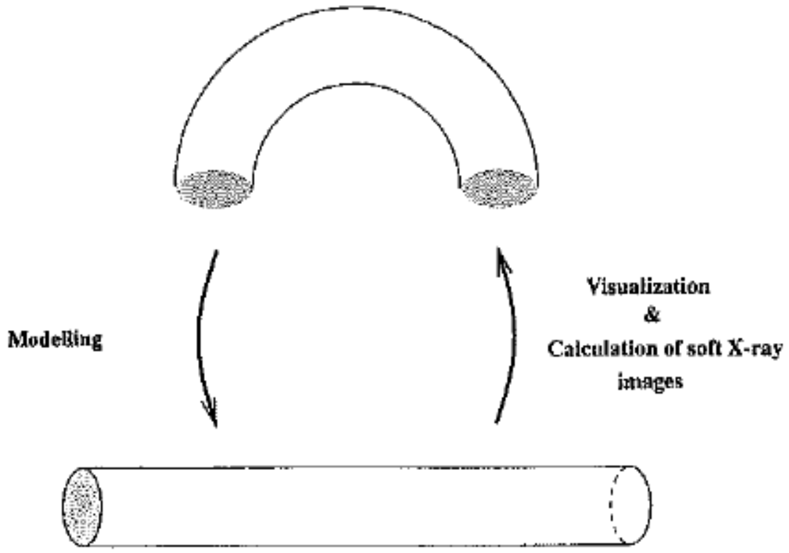
- Compare kinetic energy integrated over 3D domain with kinetic energy derived from LOS velocities (and LOS densities)
  - Only between 7 – 20% of energy ‘visible’

- Footpoint driver also contains magnetic energy
  - Visible (kinetic) energy only 3 – 10% of total energy in 3D domain (kinetic + magnetic)

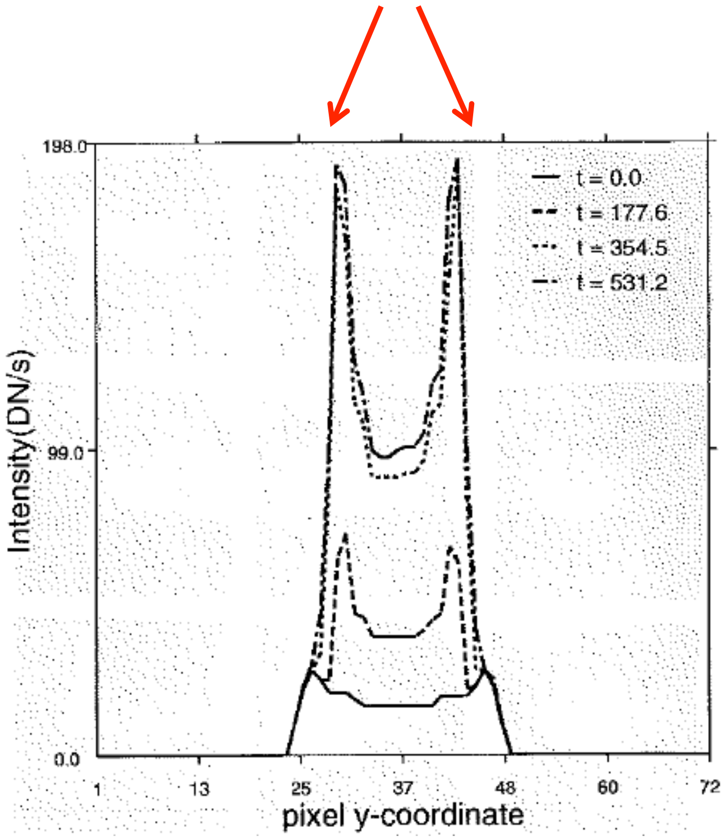
Observational Signatures of Wave Heating

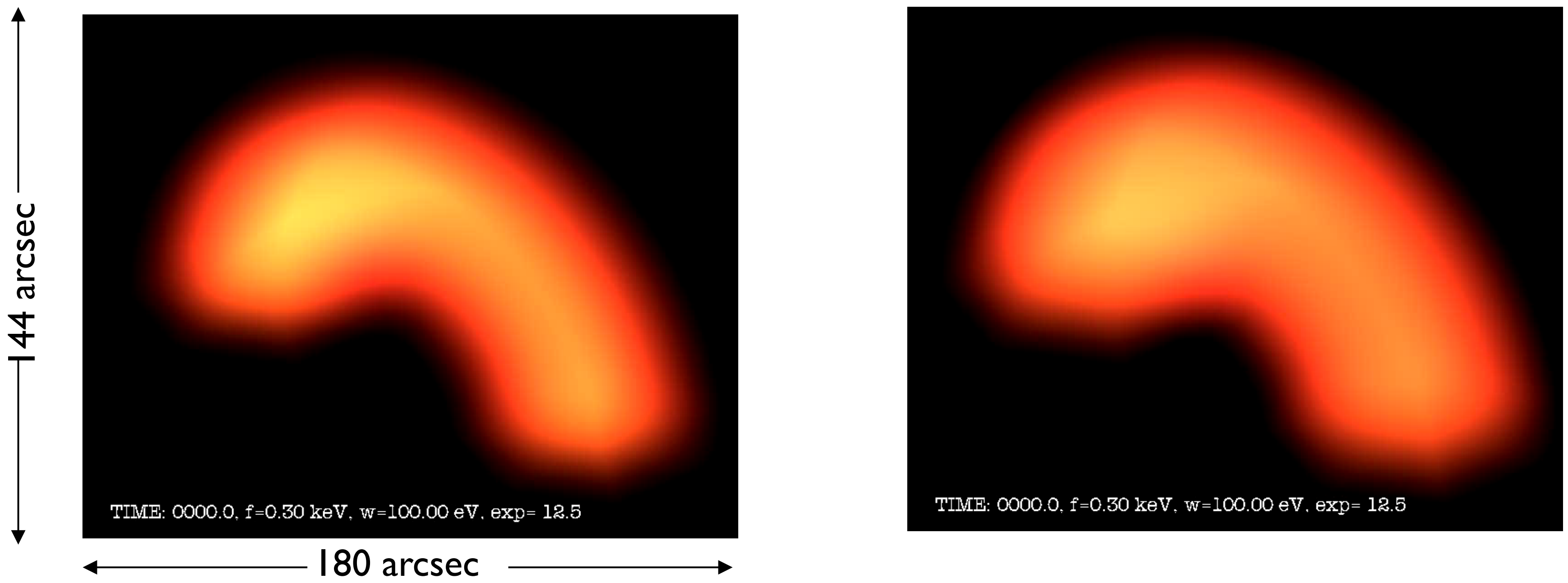
- **So what does wave heating look like?**
- Not many studies on actual observational signatures.
- *Belien et al (1996):* Visualisation of heating by resonant absorption
    - Simulated Yohkoh/SXT emission
    - Monochromatic wave: only 1 resonance layer
    - Broadband spectrum: many layers (e.g. De Groof et al 2002)

      → uniform emission?



Resonance layer





Resonance layer at r=0.5 a

Resonance layer closer to surface

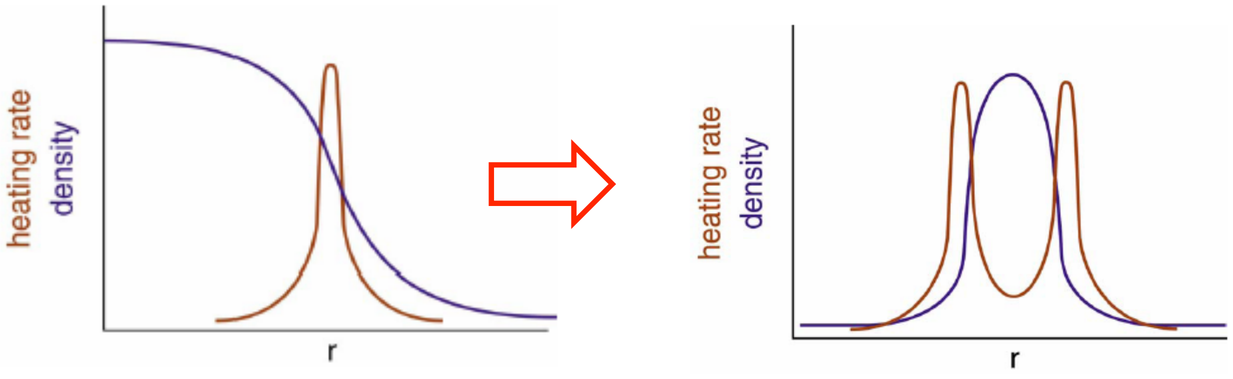
Simulated Yohkoh/SXT emission

Observational Signatures of Wave Heating

➢ **So what does wave heating look like?**

- Heating in the resonance layer should lead to chromospheric evaporation
    - Modification of the radial density profile
    - Drifting of the heating layer?

Ofman et al 1998



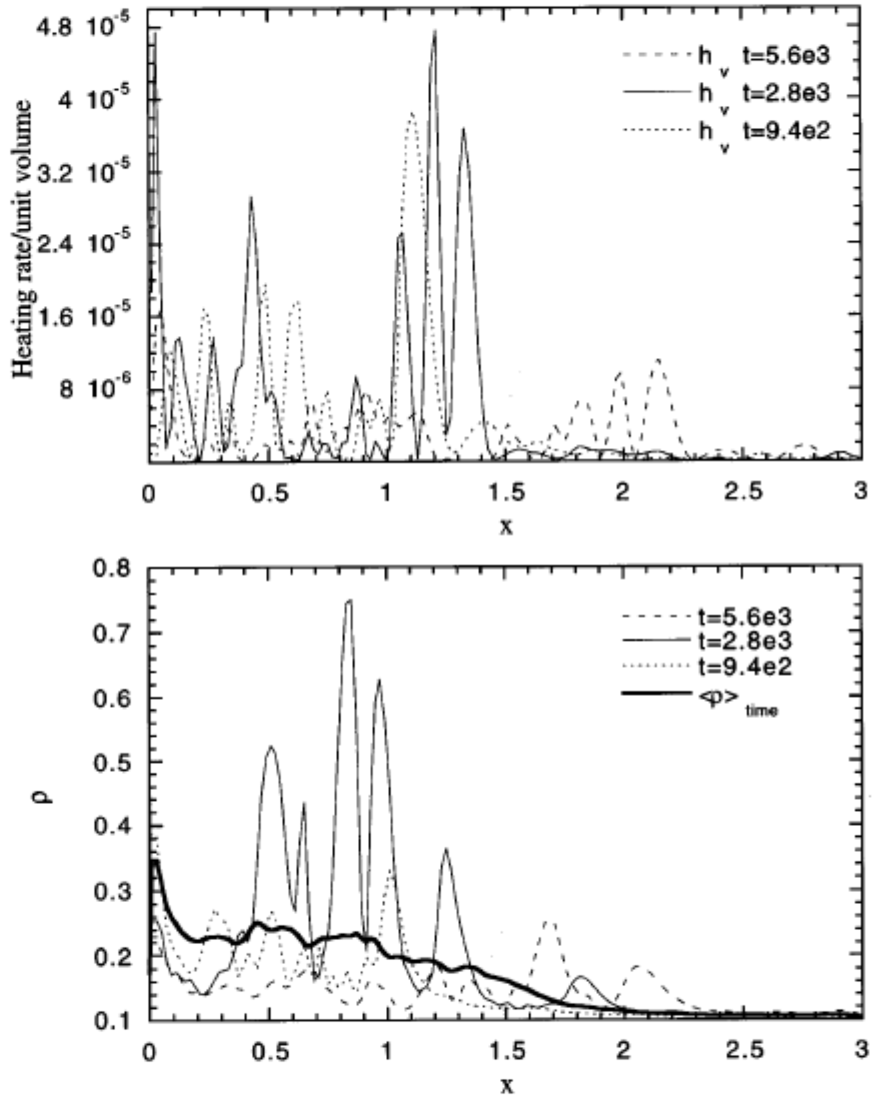
- *Ofman et al (1998):* numerical simulations of resonant absorption
    - Use scaling laws for quasi-static heating
    - Changes in density structuring because of heating/cooling
    - Volumetric heating rate:

$$Q \approx \frac{3}{7}\kappa_0 \frac{T^{7/2}}{L^2} \approx \frac{3}{4}\rho_0^2 \Lambda(T)$$

    - Multi-structured heating and density

➢ **Can wave heating look implusive?**

- Timescales?
- Difference with other heating mechanism?

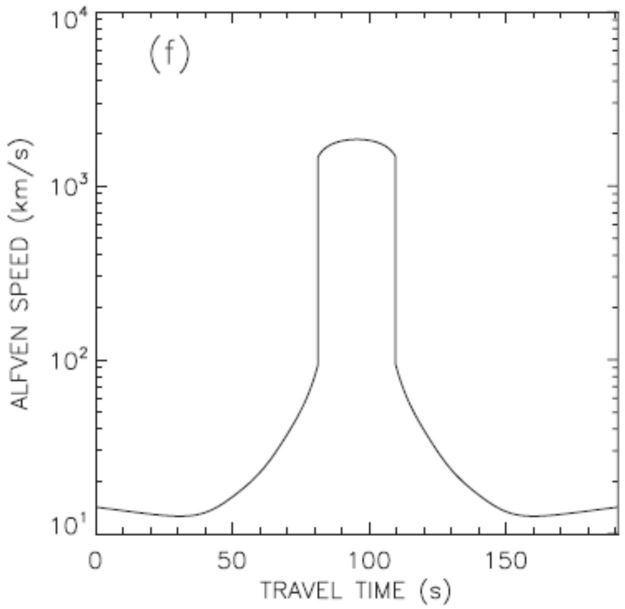


Talk Greg Kiddie

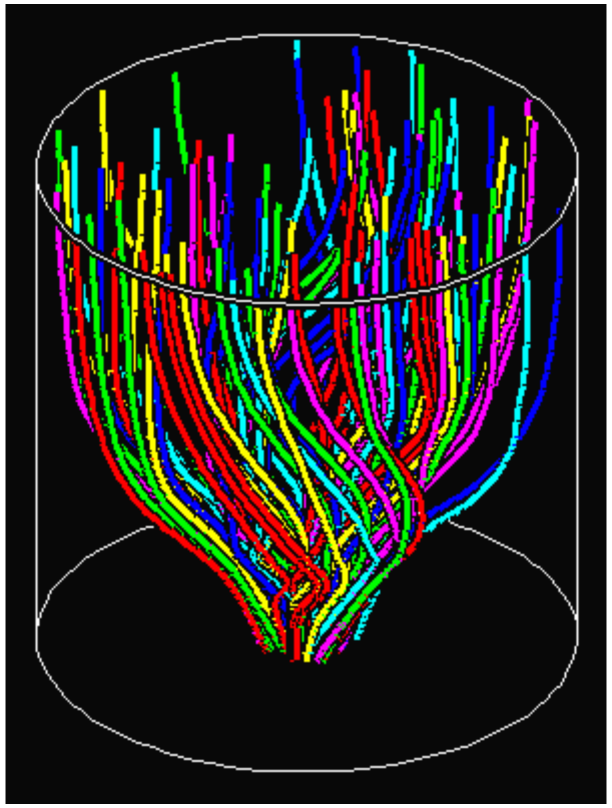
Klimchuk 2006

Observational Signatures of Wave Heating

Van Ballegooijen et al 2011

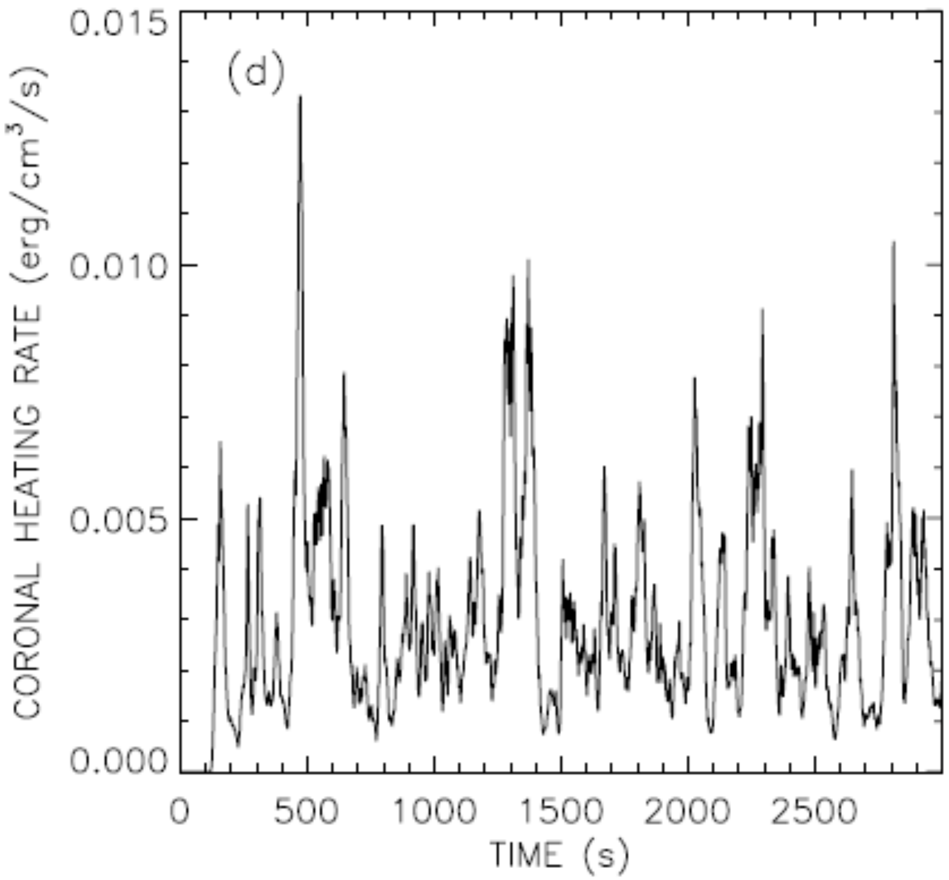


- Reduced MHD
- Small scale footpoint motions (< 100 km) - incompressible
- Assume AR flux tube maintains identity
- Strong reflection of chromosphere and TR → complex pattern of counter-propagating waves → Alfvénic turbulence
- *Coronal heating pattern similar to nanoflare storm!*



Z = 0 - 2 Mm

Z = 2 - 50 Mm



Kudoh & Shibata 1999; Mendoza-Briceno 2002,2005; Moriyasu et al 2004; Antolin & Shibata 2010; Matsumoto & Shibata 2010

Observational Signatures of Wave Heating

- Thermodynamic plasma response not included so no predictions in terms of emissions

- Predictions of heating rate in terms of footpoint motions and loop length:

$$Q_{\rm cor} \approx 2.97 \times 10^{-3} \left(0.45 + \frac{33}{\tau_0}\right) \left(\frac{\omega_0}{0.04\ {\rm s}^{-1}}\right)^{1.65} \times \left(\frac{L_{\rm cor}}{50\ {\rm Mm}}\right)^{-0.92} \ {\rm erg\ cm^{-3}\ s^{-1}},$$

- Heating rate dependence of magnetic field strength

$$Q_{\rm chrom} \approx 6.49 \times 10^{-1} \left(\frac{B_{\rm cor}}{50\ {\rm G}}\right)^{0.47} \ {\rm erg\ cm^{-3}\ s^{-1}}$$

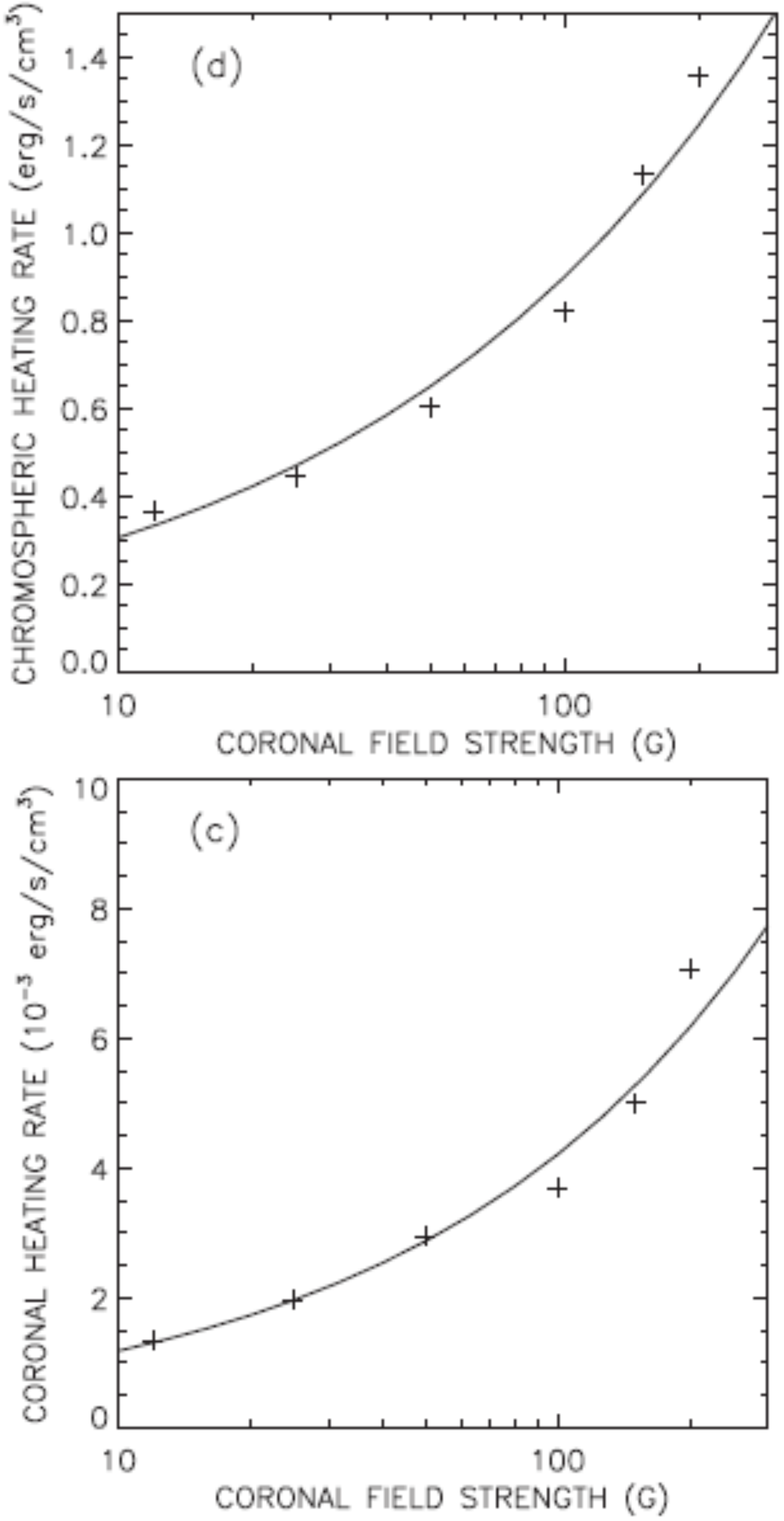
$$Q_{\rm cor} \approx 2.88 \times 10^{-3} \left(\frac{B_{\rm cor}}{50\ {\rm G}}\right)^{0.55} \ {\rm erg\ cm^{-3}\ s^{-1}}$$

➢ Coronal heating rate increases for
  — Stronger |B|
  — Shorter loops

❖ Most heating in lower atmosphere (< 10% energy transmitted)
  ~ De Pontieu et al (2009)

❖ Coronal part likely to be thermally stable
  ~ Klimchuk et al (2010)

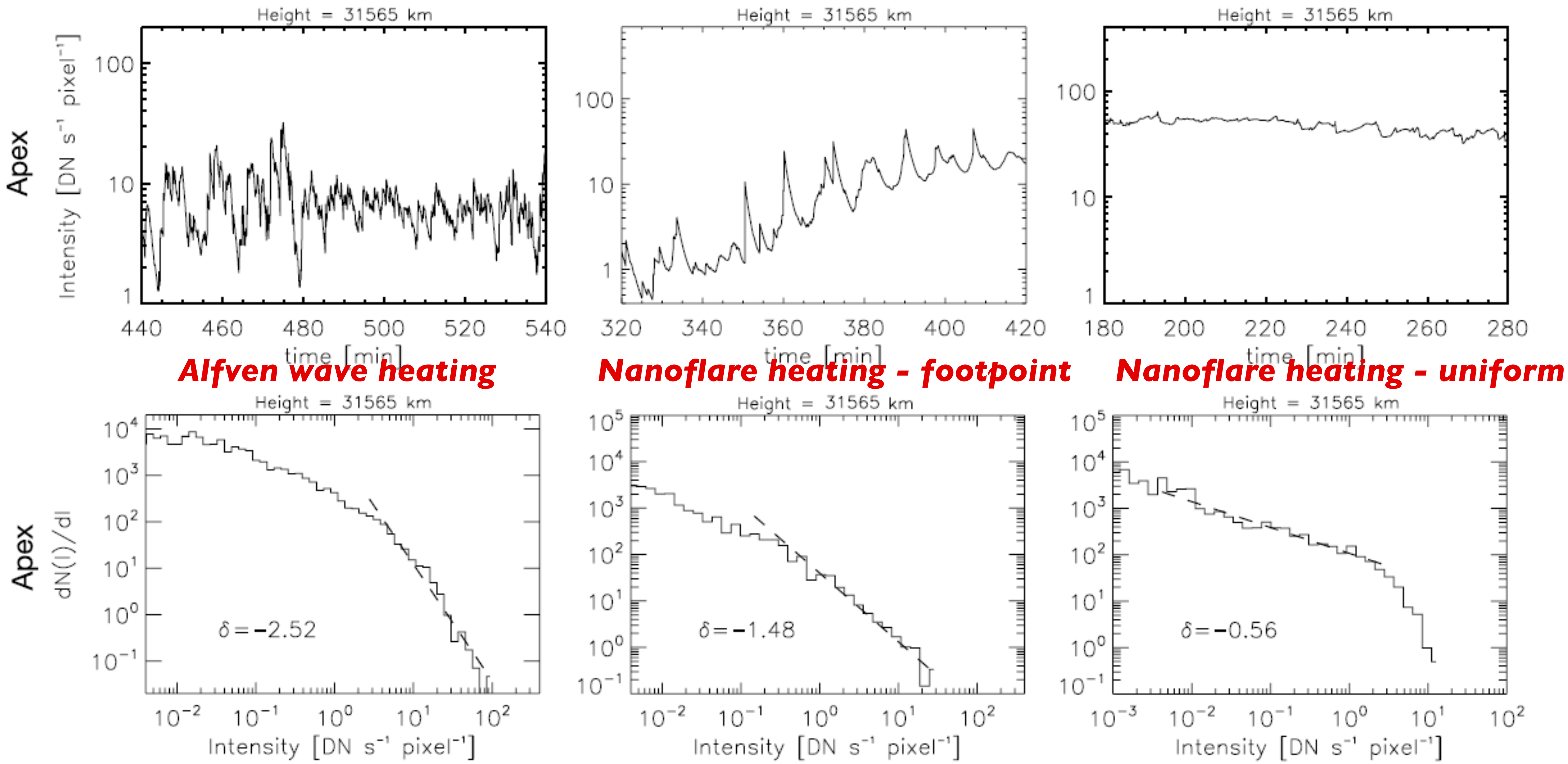
Van Ballegooijen et al 2011



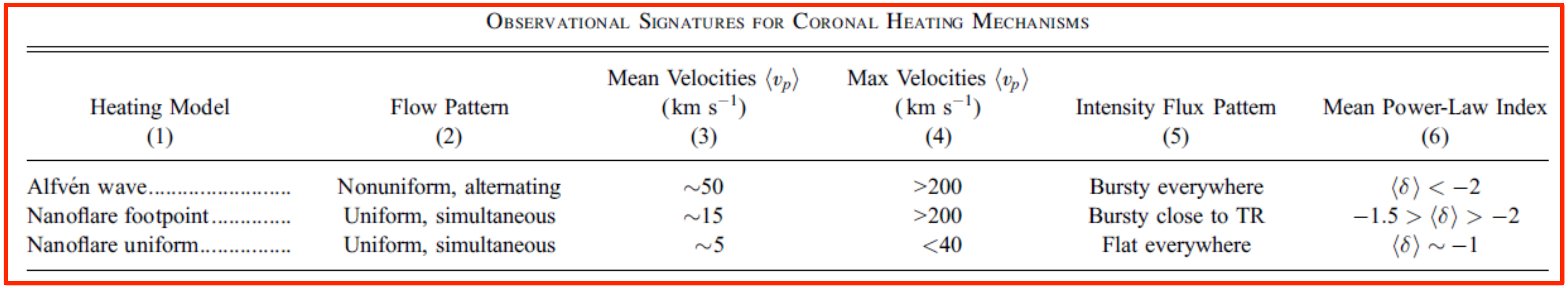
Observational Signatures of Wave Heating

- 1.5D model to try and distinguish between waves and nanoflares

Antolin et al 2008



Alfven wave heating **Nanoflare heating - footpoint** **Nanoflare heating - uniform**



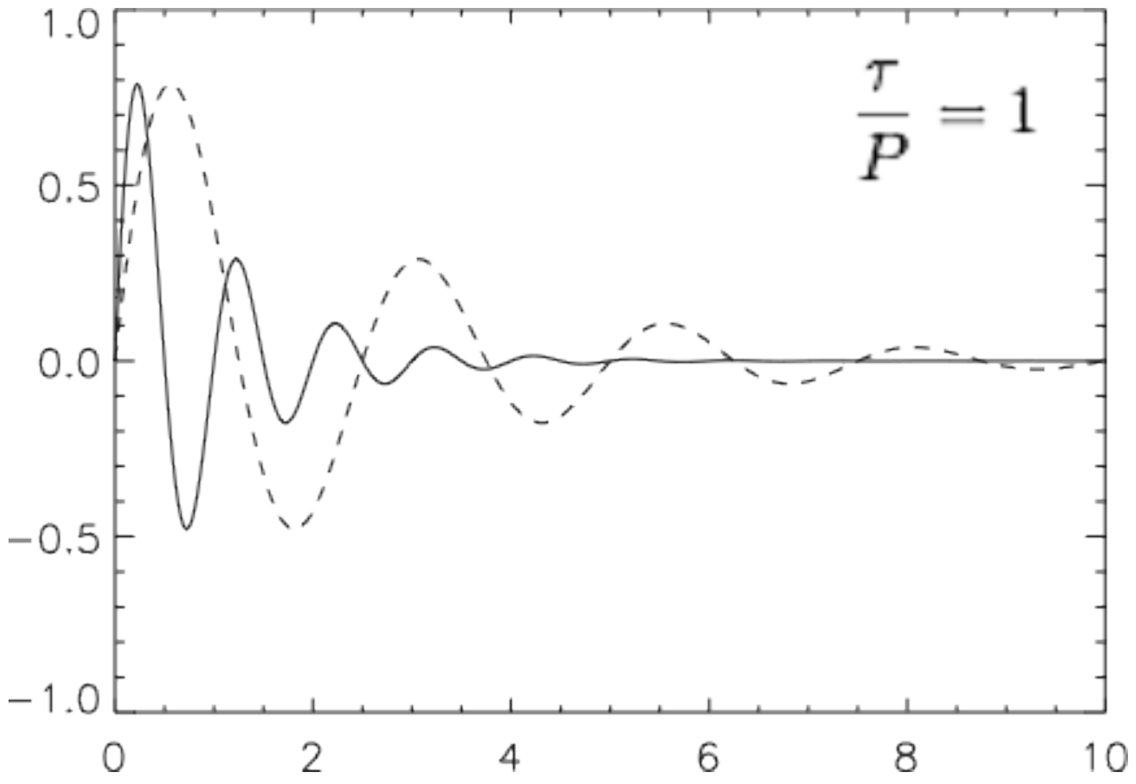
OBSERVATIONAL SIGNATURES FOR CORONAL HEATING MECHANISMS

Heating Model (1)	Flow Pattern (2)	Mean Velocities $\langle v_p \rangle$ (km s^{-1}) (3)	Max Velocities $\langle v_p \rangle$ (km s^{-1}) (4)	Intensity Flux Pattern (5)	Mean Power-Law Index (6)
Alfvén wave........................	Nonuniform, alternating	$\sim$50	>200	Bursty everywhere	$\langle \delta \rangle < -2$
Nanoflare footpoint.............	Uniform, simultaneous	$\sim$15	>200	Bursty close to TR	$-1.5 > \langle \delta \rangle > -2$
Nanoflare uniform................	Uniform, simultaneous	$\sim$5	<40	Flat everywhere	$\langle \delta \rangle \sim -1$

Moriyasu et al 2004; Taroyan et al 2007; Taroyan & Erdelyi 2009

Mode Coupling – Frequency Filtering

Harmonic Driver

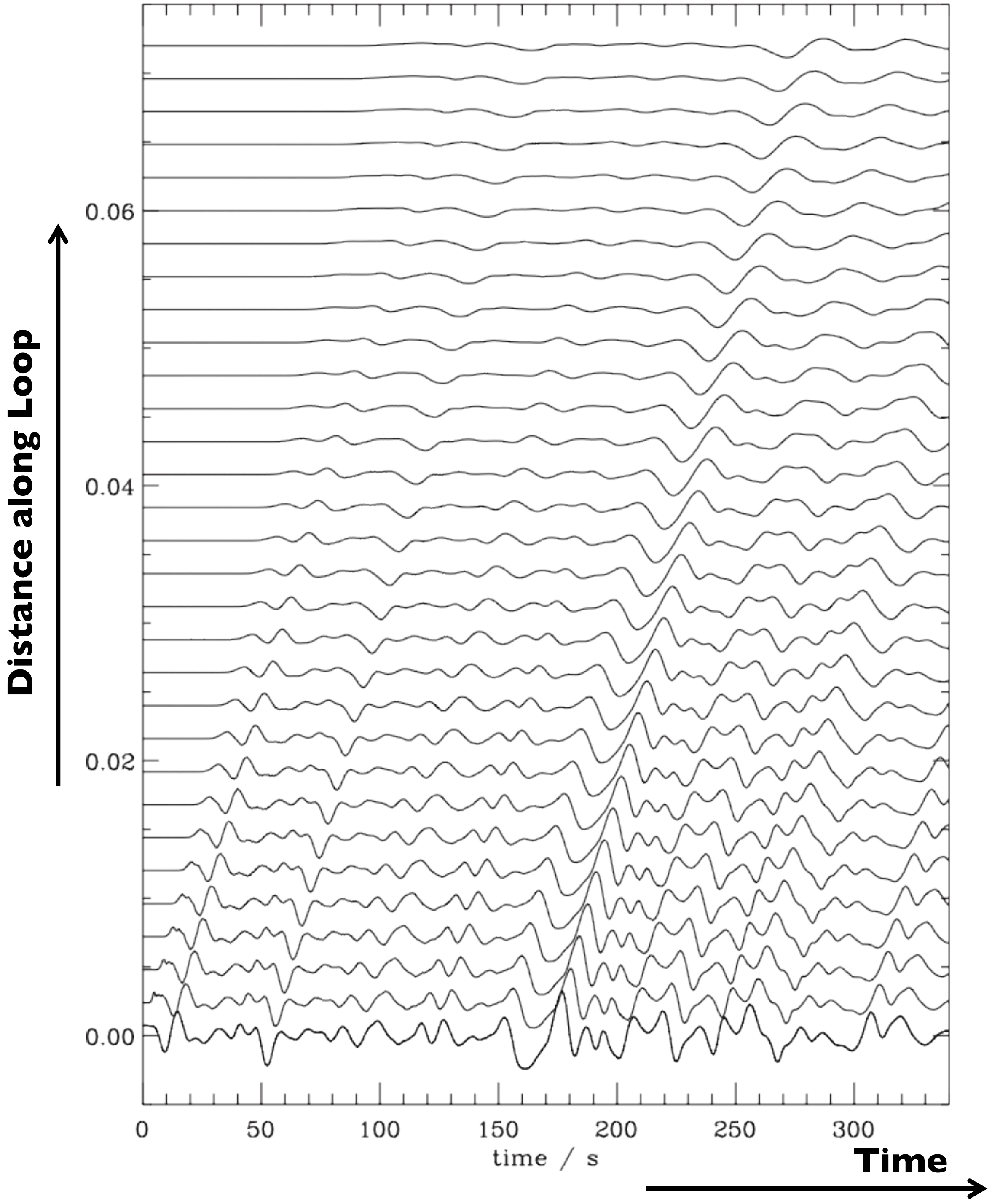


$$\frac{\tau}{P} = C\,\frac{a}{l}\,\frac{\rho_0 + \rho_e}{\rho_0 - \rho_e}$$

$$\boxed{\tau \sim P \;\; \& \;\; L_d = V_g \tau \;\; \Rightarrow \;\; L_d \sim P}$$

- Frequency dependence evident in CoMP data

Broadband Driver



Ruderman & Roberts 2002;Verth et al 2010; Terradas et al 2010; Pascoe et al 2010, 2012

Conclusions/Future Directions

- Observations: waves present beyond doubt in a wide range of structures in all layers of the solar atmosphere.
- Wave heating has come full circle and is now back at the forefront of the coronal heating debate.
    - Vast amount of literature!
- Theoretical/numerical modelling needs to catch up:
    - Issues with mode identification and complexity of models
    - Wave models need to include highly dynamic ‘wave guides’.
    - More work needed to identify observational signatures.

Ofman 2009; Parnell & De Moortel 2012; De Moortel & Nakariakov 2012